Working Group: Shell Evolution

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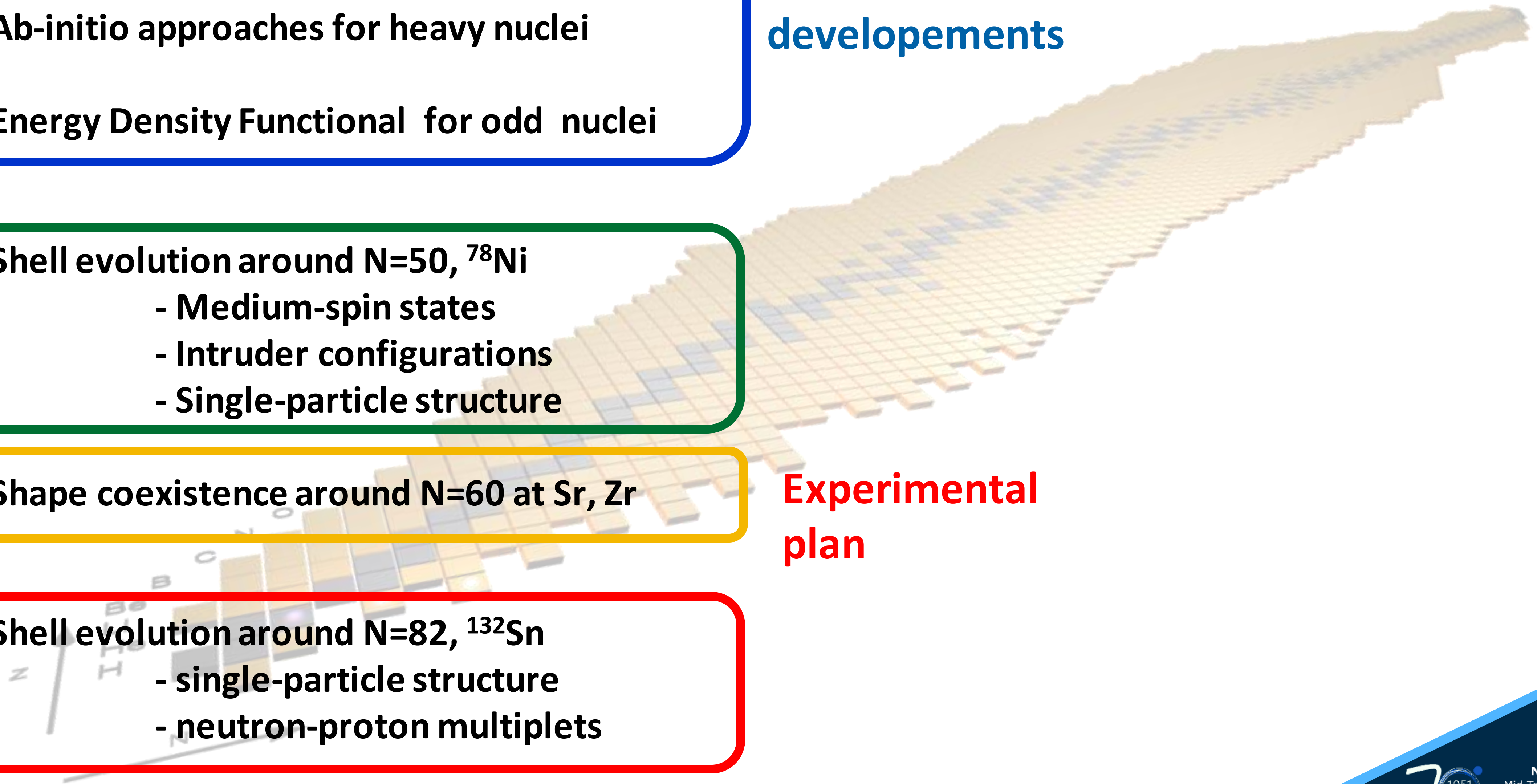
Outline



- **Shell structure: the limits of its observability**
- **Ab-initio approaches for heavy nuclei**
- **Energy Density Functional for odd nuclei**

Theoretical developements

Experimental plan

- **Shell evolution around N=50, ^{78}Ni**
  - **- Medium-spin states**
  - **- Intruder configurations**
  - **- Single-particle structure**

- **Shape coexistence around N=60 at Sr, Zr**

- **Shell evolution around N=82, ^{132}Sn**
  - **- single-particle structure**
  - **- neutron-proton multiplets**

Magic numbers ?!

*“Impression I was certain of it. I was just telling myself that, since **I was impressed**, there had to be **some impression in it** — and what freedom, what ease of workmanship! A preliminary drawing for a wallpaper pattern is more finished than this seascape.”*

Louis Leroy, Le Charivari on 25 April 1874

Claude Monet's **Impression**, Sunrise (Impression, soleil levant)

It was actually **Eugene Paul Wigner** who coined the term “magic number”.
The physicists community at that time favored the **liquid-drop model**.
“**Eugene Wigner** too believed in the liquid drop model, but he recognized, from the work of **Maria Mayer**, the very strong **evidence for the closed shells**. It seemed a little like **magic to him**, and that is how the words ‘Magic Numbers’ were coined.”,

said Steven A. Moszkowski, who was a student of Maria Goeppert-Mayer, in a talk presented at the APS meeting in Indianapolis, May 4, 1996

G. Audi, International Journal of Mass Spectrometry 251 (2006) 85–94

Theoretical developements in a mid-term timescale

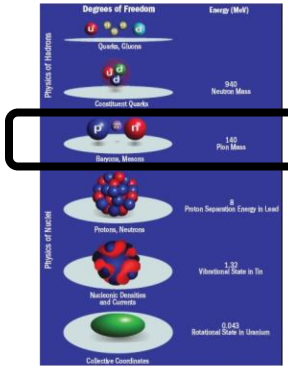
Experimental data vs theory – T. Duguet

Theoretical schemes based on quantum mechanics

e.g. 1) ab initio method
2) valence-space shell model

Degrees of freedom

1) and 2) point-like nucleons



Kinematical space

1) H_A with p in [0,150] MeV
2) H_A with e in e_F +/- few MeV

Hamiltonian

1) χEFT
2) valence-space reduction

Dynamical equations

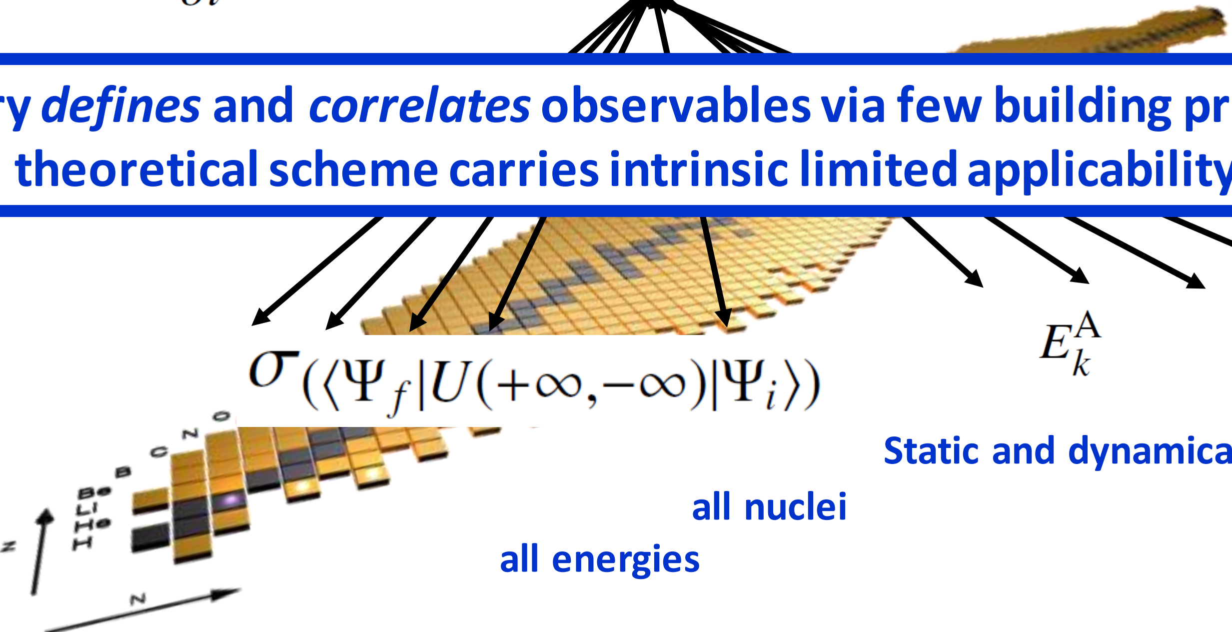
$$i\hbar\frac{\partial}{\partial t}|\Psi(t)\rangle = H|\Psi(t)\rangle \quad \& \quad H|\Psi_k^A\rangle = E_k^A|\Psi_k^A\rangle$$

Theory *defines* and *correlates* observables via few building principles
Each theoretical scheme carries intrinsic limited applicability range

Many-body observables

$$\sigma(\langle\Psi_f|U(+\infty,-\infty)|\Psi_i\rangle) \qquad E_k^A \qquad \langle\Psi_k^A|O|\Psi_k^A\rangle$$

Empirical world



Static and dynamical properties for

all nuclei

all energies

Nuclear shell structure – T. Duguet

Nuclear shell structure

Goal is to further *correlate*
a large sequence of A-body observables (mass, 2^+_1 energy, one-nucleon sep. energies…)
to a simpler one-body quantity

in order to deliver a *simplified* rationale of complex empirical patterns

Effective single-particle energies

Uniquely-defined mathematically [Baranger, 1970]

Values however depend on / change with theoretical [Duguet et al. 2015]

1) scheme, e.g. ab initio vs valence-space shell model
*2) scale = **unitary freedom of quantum mechanics***

Actual observable do not /must not!

➲ *shell structure*

*a) is **not observable***
*b) exists **only** within theory (**not** to be « extracted » from empirical data)*
c) is to be consistently computed through one given theoretical scheme&scale
*d) delivers a **simplified rationale depending on theoretical scheme&scale***

Requirement for mesurements – T. Duguet

ESPE

$$\mathbf{h}^{\text{cent}} \equiv \sum_{\mu\in\mathcal{H}_{A+1}} \boxed{\mathbf{S}^{+}_{\mu}}\boxed{E^{+}_{\mu}} + \sum_{\nu\in\mathcal{H}_{A-1}} \boxed{\mathbf{S}^{-}_{\nu}}\boxed{E^{-}_{\nu}}$$

Diagonalization

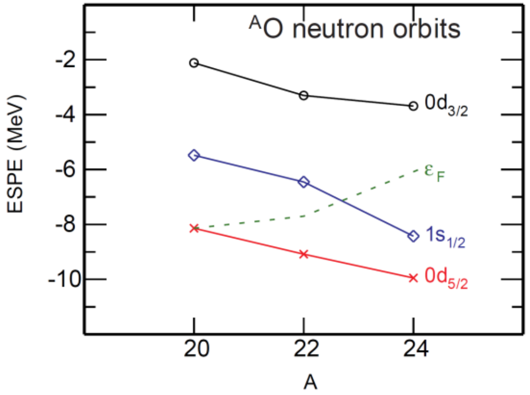
$$e^{\text{cent}}_{p} \equiv \sum_{\mu\in\mathcal{H}_{A+1}} S^{+pp}_{\mu} E^{+}_{\mu} + \sum_{\nu\in\mathcal{H}_{A-1}} S^{-pp}_{\nu} E^{-}_{\nu}$$

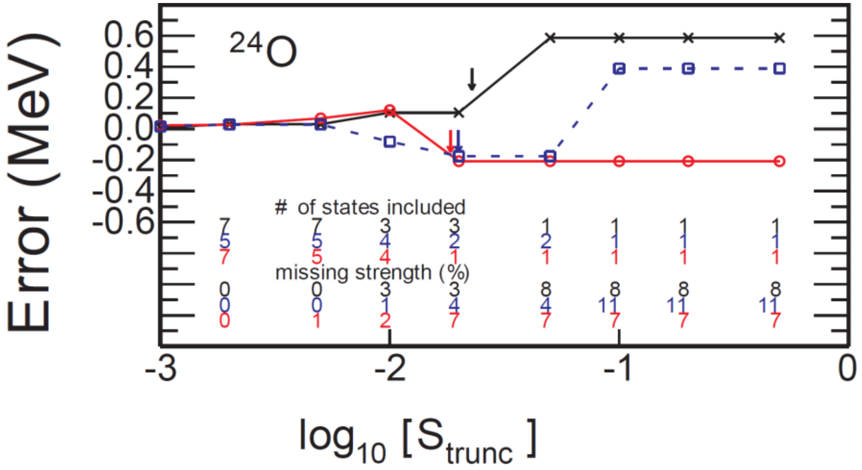
One-nucleon separation energies = observables

Spectroscopic probability matrices (~SFs) **= non observable = only come from/depend on theory**

Example within valence shell model theoretical scheme

[Signoracci, Duguet, unpublished]





Error on ESPEs down to ~200keV requires

$E_k^{A\pm1}$ *up to ~10MeV in main channel*

$S_k^{\pm pp}$ *down to few %*

At least main state in secondary channel

Theory shall be best tested/validated

via one-nucleon addition/removal exp

up to large excitation energies

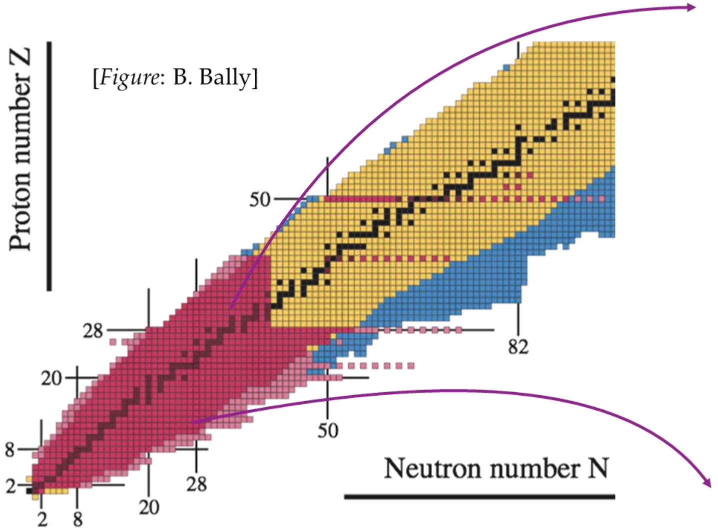
down to small cross sections

in both reaction channels

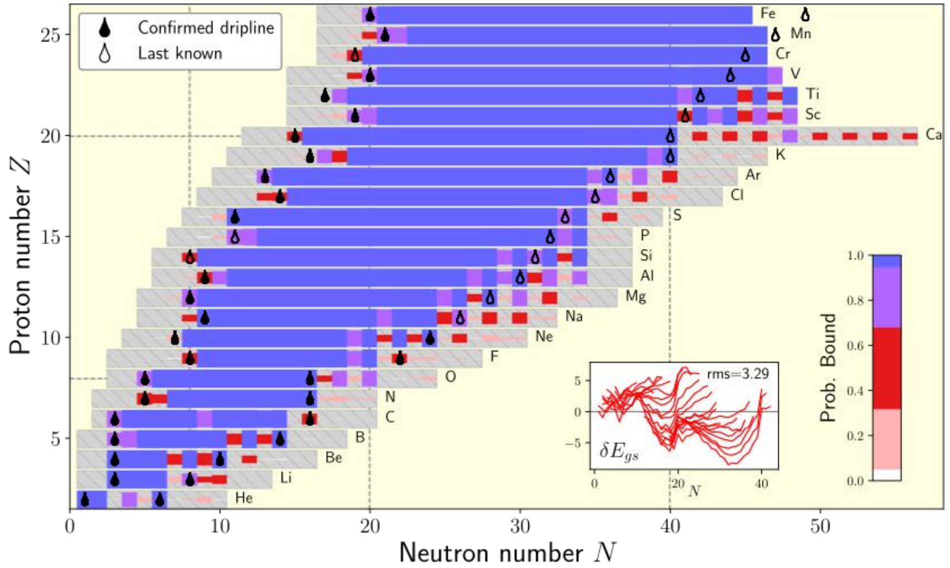
Challenging but necessary in exotic nuclei

Ab-initio methods: State of the art

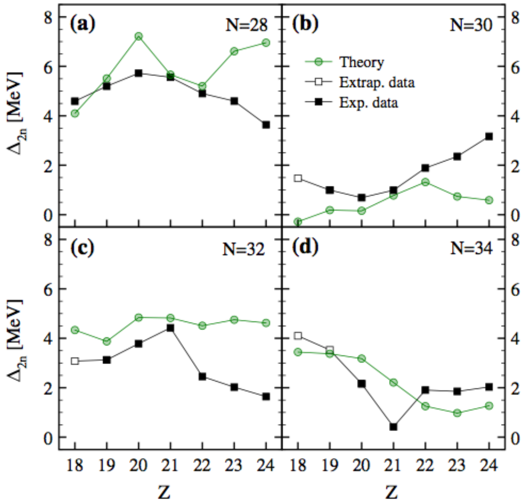
Steady development over last few years



Valence space (shell model) → systematic up to iron



[Stroberg *et al.*, 2021]



Full space → focus around semi-magic, i.e. Z=20

Current frontiers

- ○ **Extension to heavier nuclei**

→ Exponential (VS) vs polynomial (FS) scaling

- ○ **Inclusion of deformation**
- ○ **Enlarge accessible observables**

Perspectives

◉ Around *Z*=20 → Precision calculations

- ○ Revisit evolution of magicity e.g. along *N*=28-34 isotones
- ○ Refine nuclear **Hamiltonians** (Bayesian analysis, emulators, …)

◉ Around *N*=50 → Discovery calculations

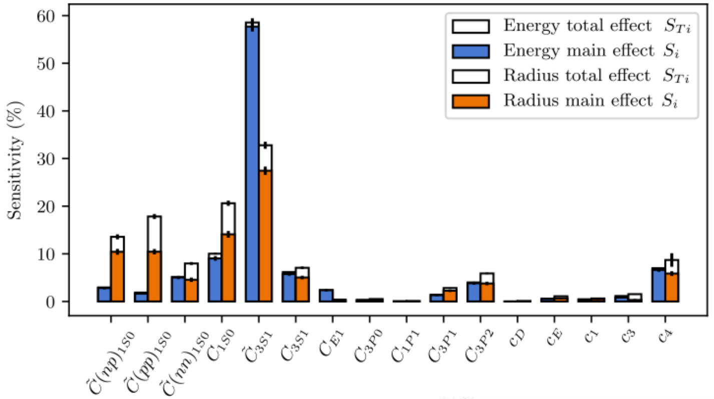
- ○ Probe theoretical description of deformation and **collectivity**
- ○ Fully develop machinery for **spectroscopy of complex nuclei**

◉ Around *N*=82 → Exploratory calculations

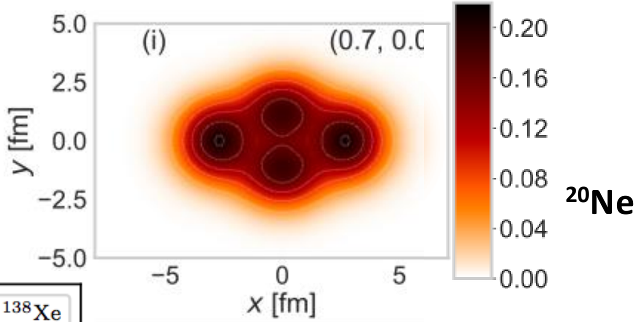
- ○ **Innovative computational techniques** required
- ○ Few flagship measurements might motivate pivot applications
- ○ First attempts very successful in reproducing e$^-$ scattering data

◉ Different and complementary observables will be needed to address

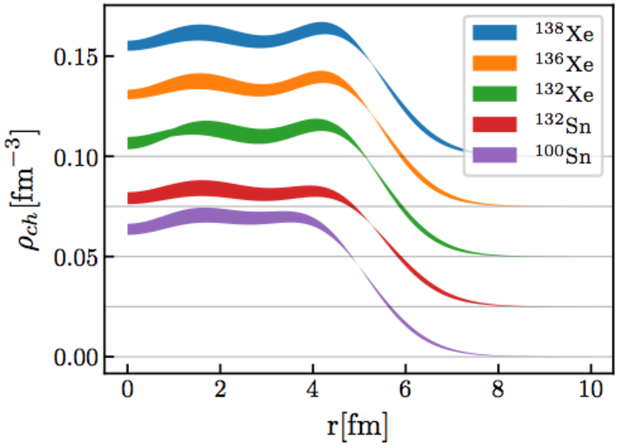
- ○ Ground-state properties (masses, charge radii, …)
- ○ **Excited state energies** (e.g., 2+) and associated **decay probabilities**
- ○ Cross sections & separation energies for **one-nucleon addition/removal**



[Ekström *et al.*, 2019]



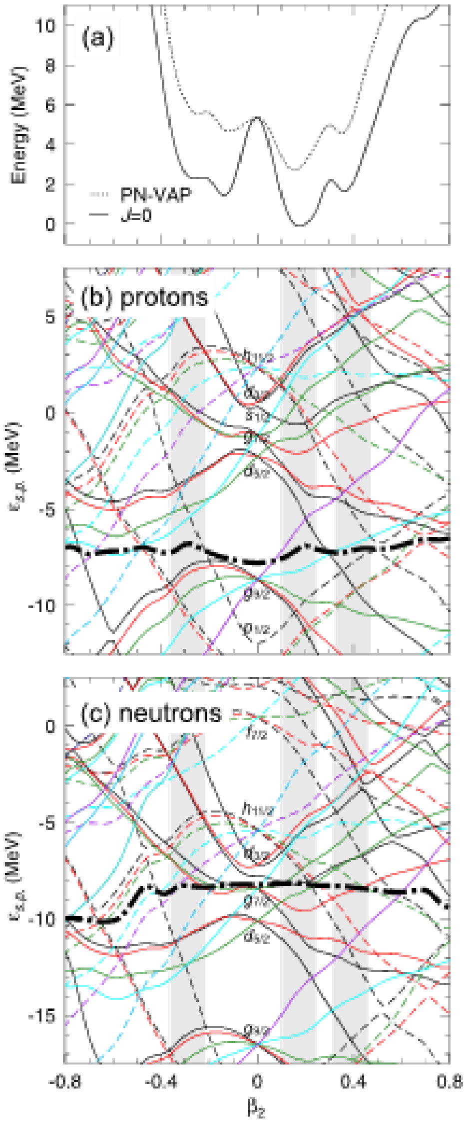
[Frosini *et al.*, 2022]

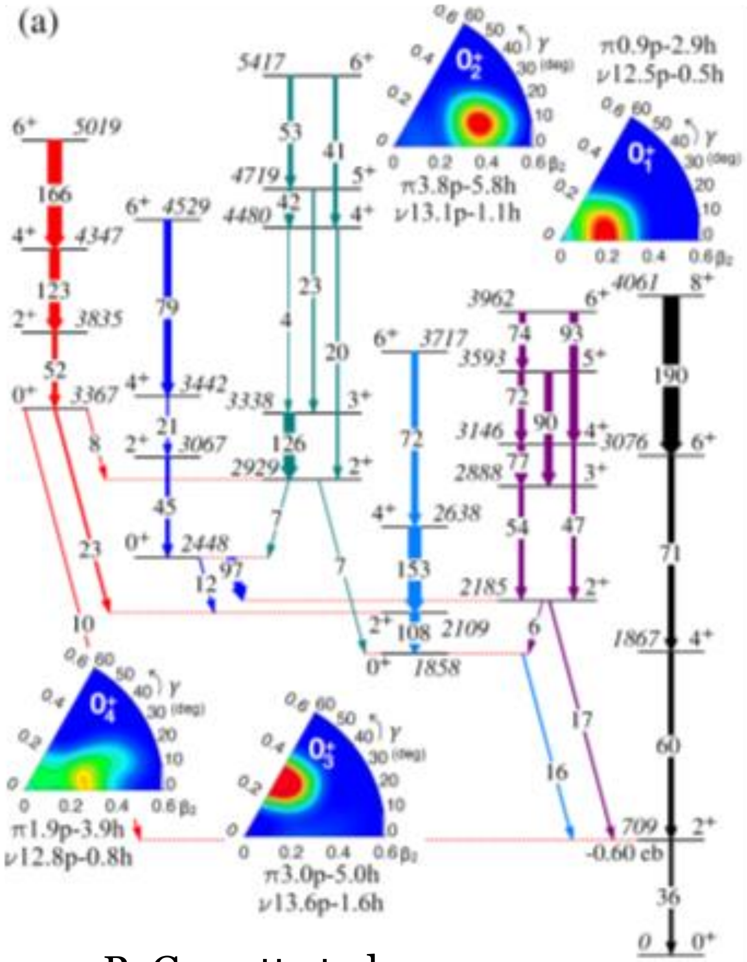


[Arthuis *et al.*, *Phys. Rev. Lett. 125* 2020]

Energy density functional methods

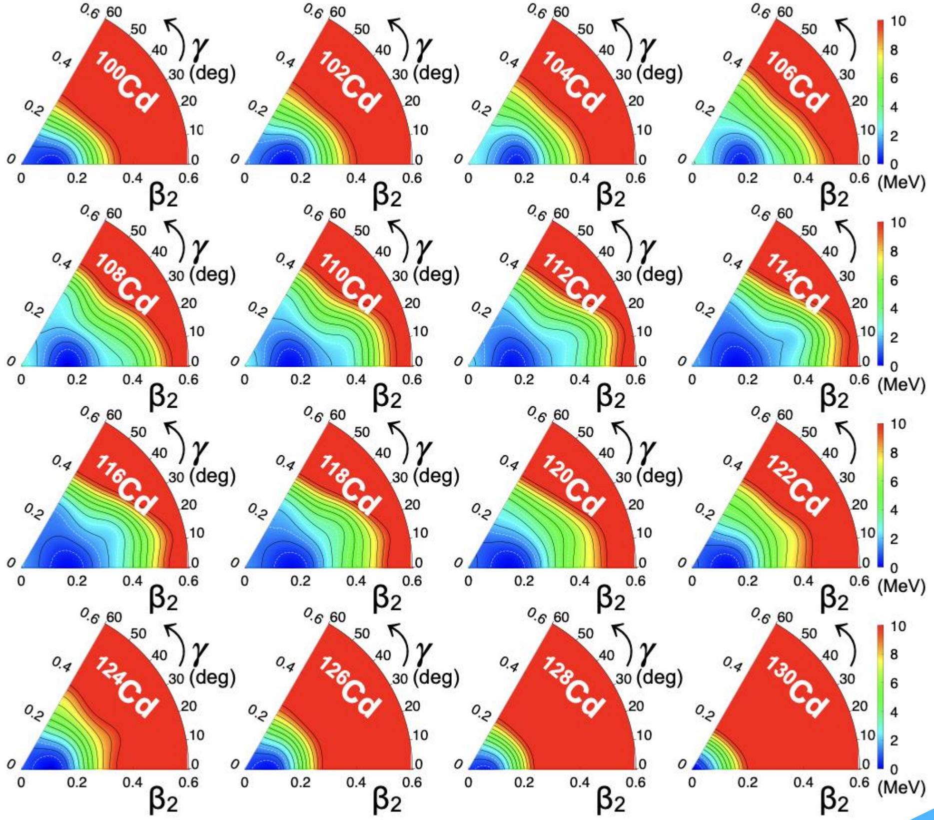
EDF calculations for even-even systems: Routinely performed to study masses, radii, excitation energies and transition probabilities including beyond-mean-field effects.





P. Garrett et al.

^{110}Cd



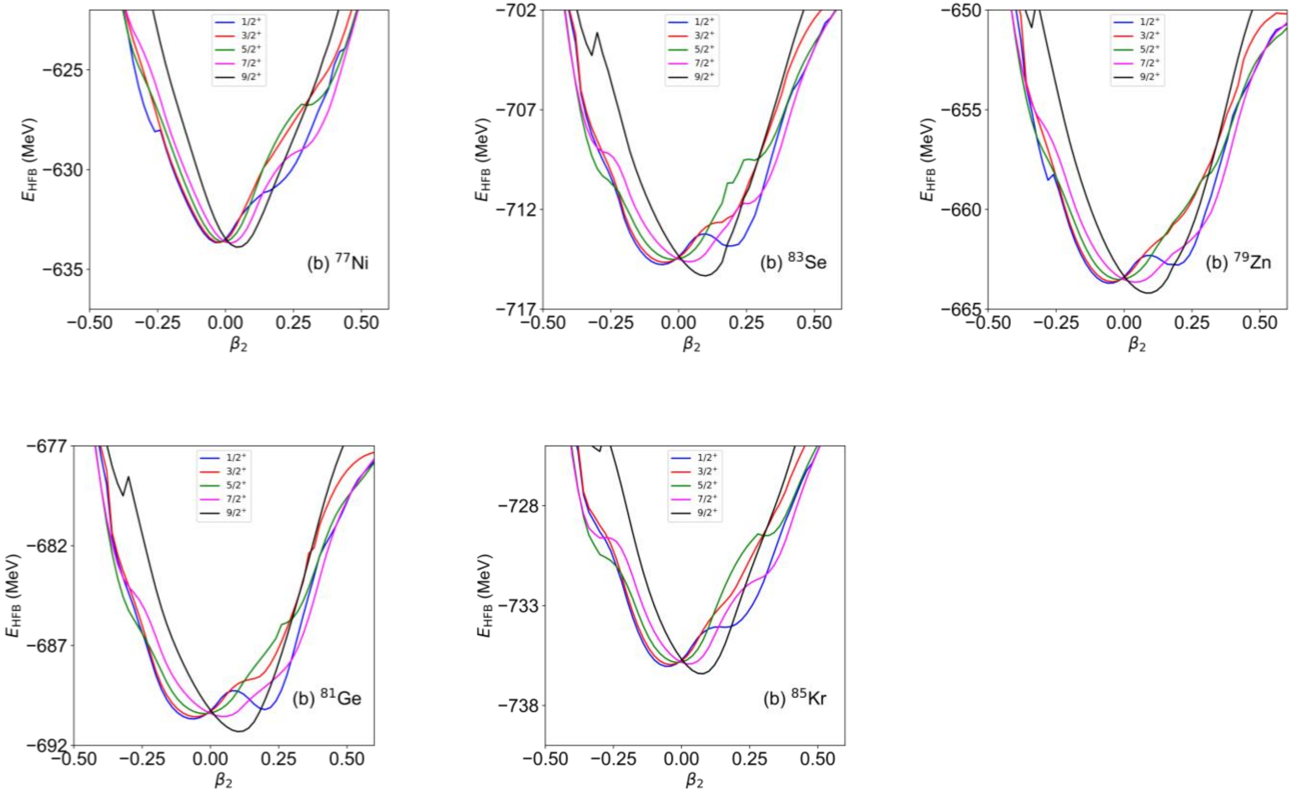
Energy density functional – T. Rodriguez

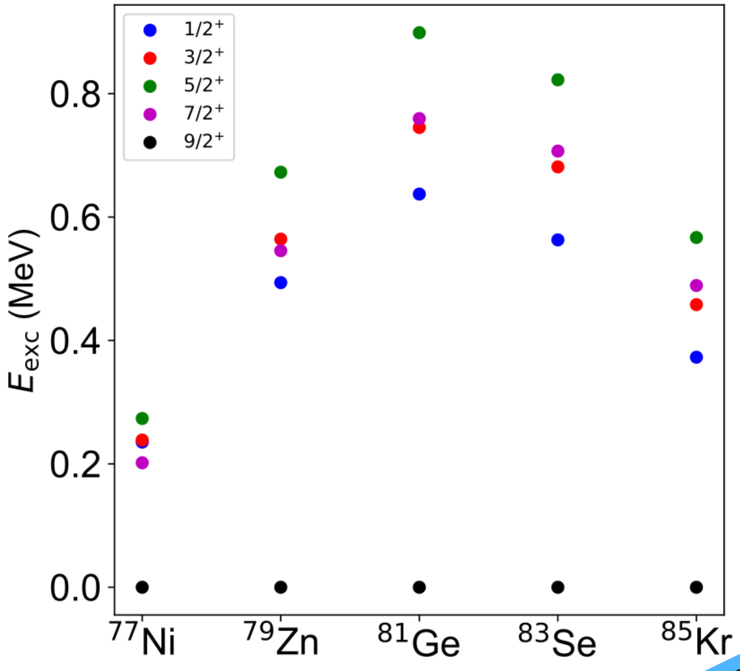
EDF calculations for odd-systems (of interest for the study of the shell evolution): Challenging!

➥ Blocking effect ⇒ time-reversal symmetry breaking ⇒ modification of the existing EDF solvers + large increase of the computational time ⇒ very few applications with beyond-mean-field effects (e.g., Bally et al., Borrajo et al.) ⇒ without BMF effects is difficult to compare directly with experimental data

➥ Pragmatic option for global analyses: mean-field calculations with blocking

Example: N=49 isotopes with axial Gogny D1M close to ^{78}Ni

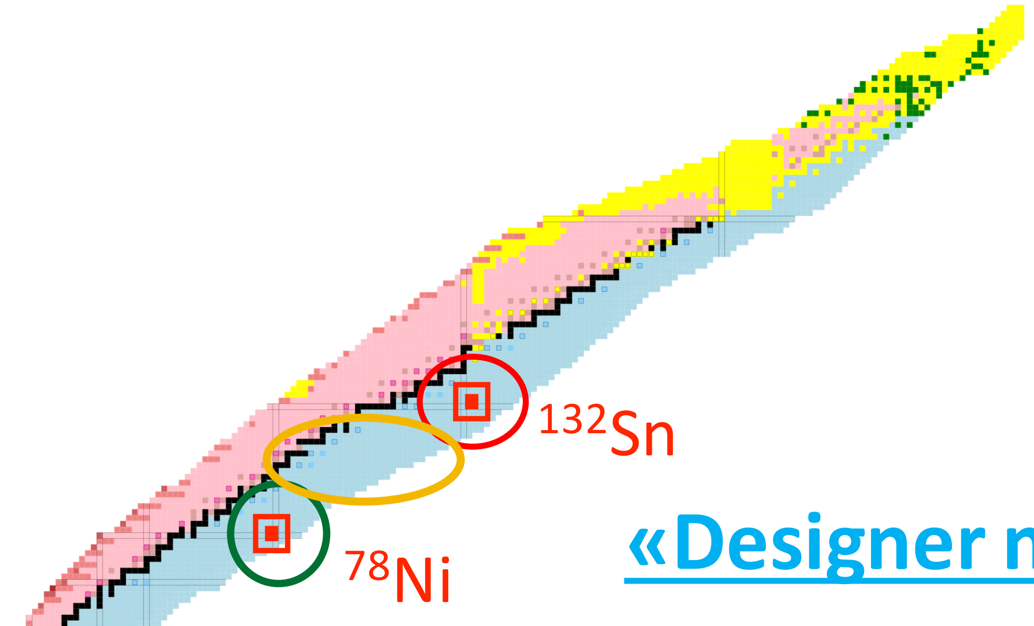




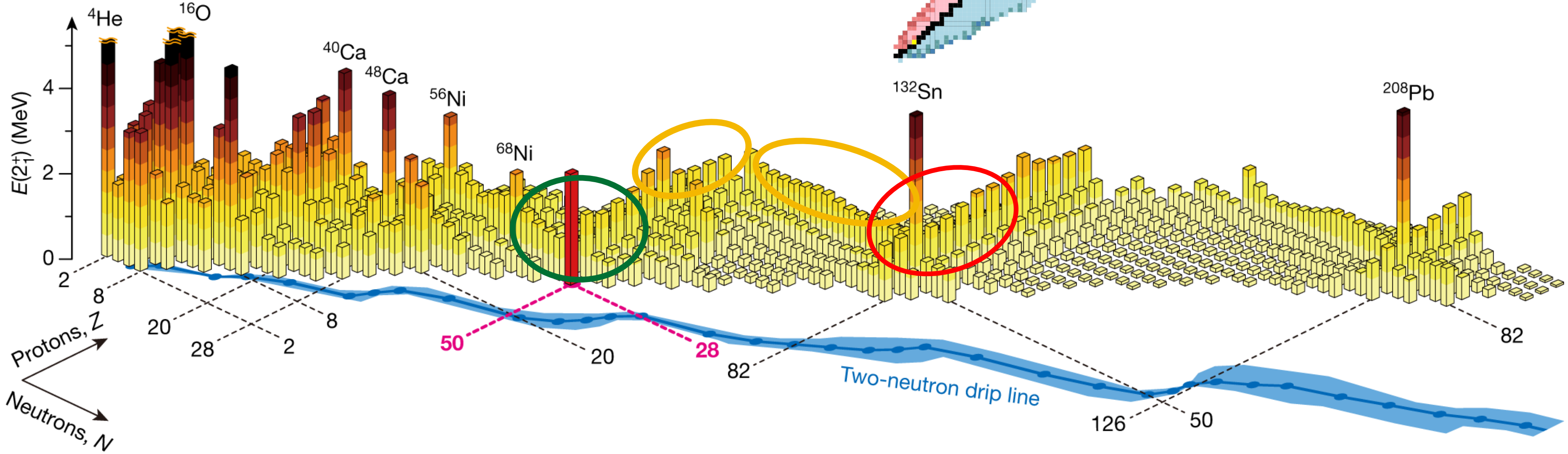
Experimental possibilities in a mid-term timescale

Designer nuclei

- **Shell evolution around ^{78}Ni**
- **Deformation and shape coexistence**
- **Shell evolution around ^{132}Sn**

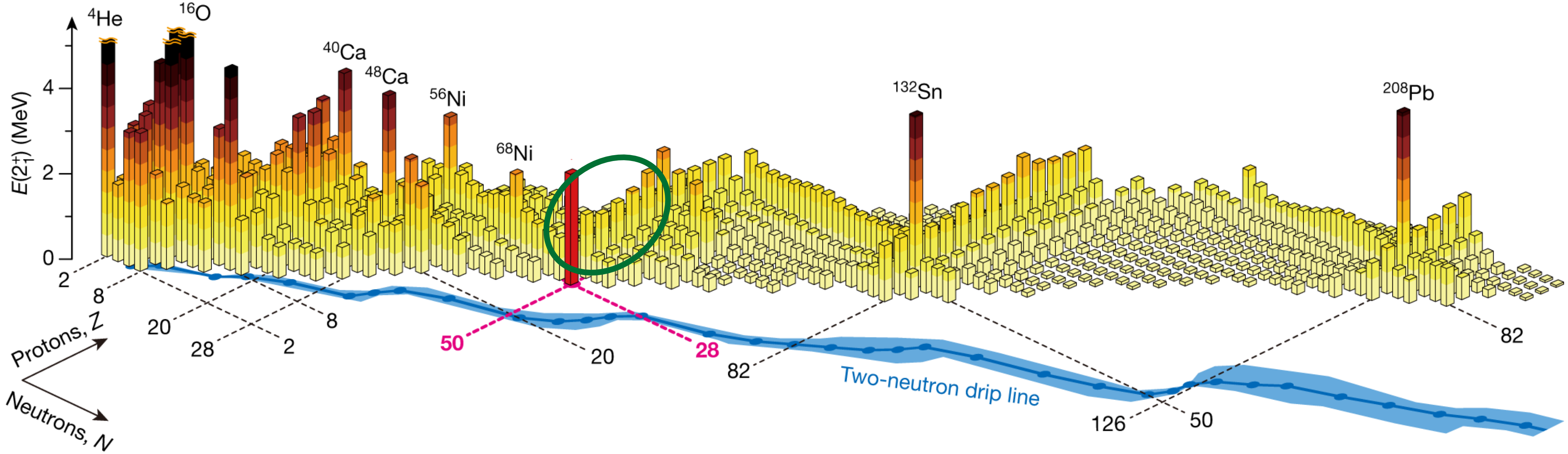


«Designer nuclei»

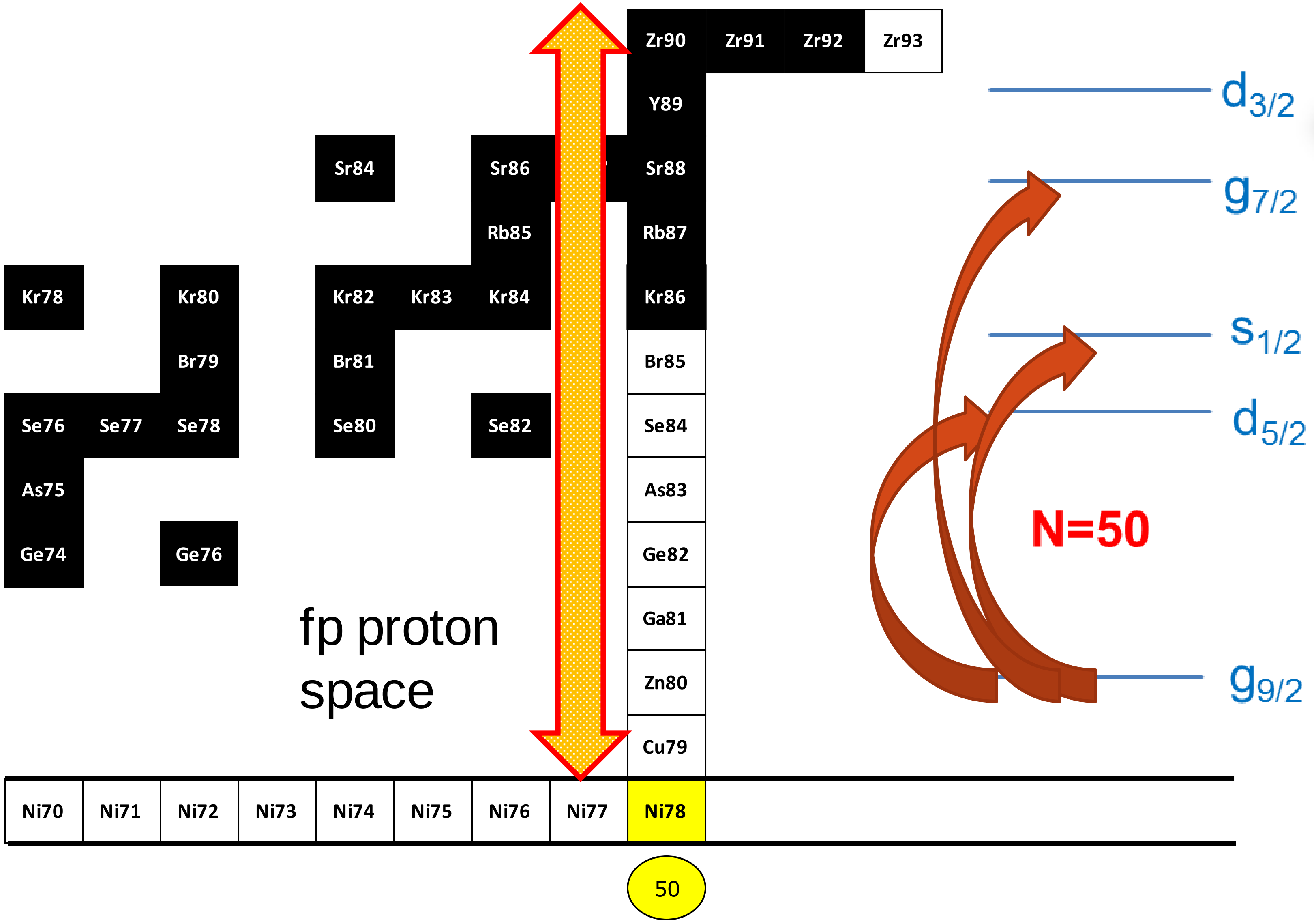


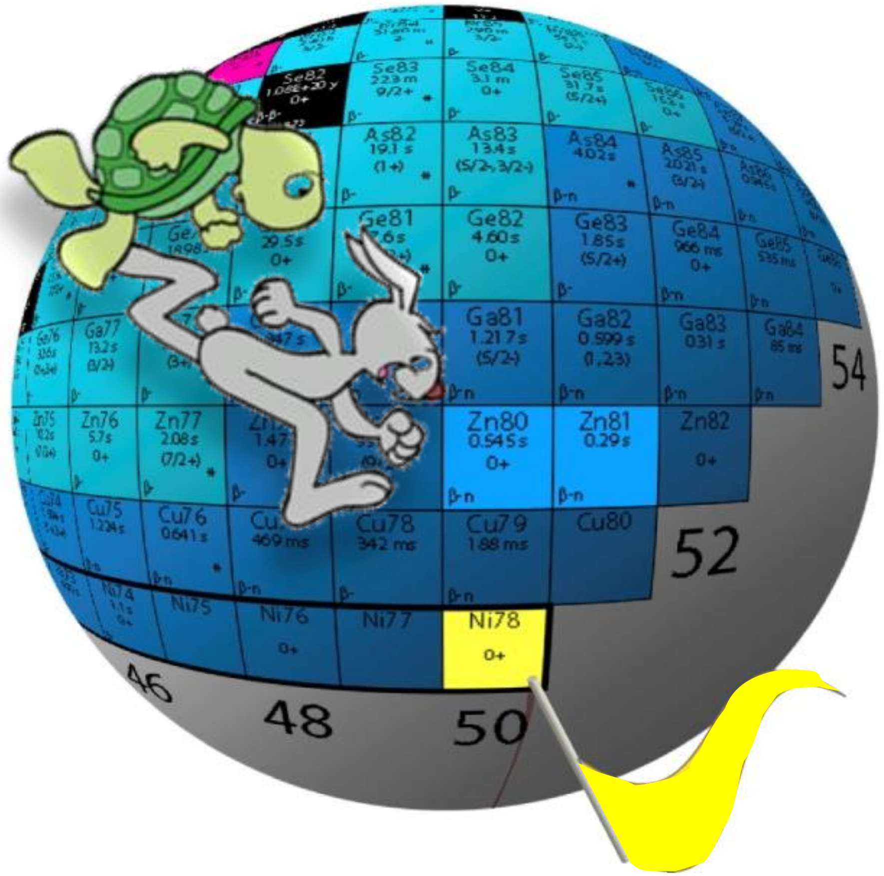
R. Taniuchi et al., Nature 569, 53–58 (2019)

The N=50 region close to ^{78}Ni



The N=50 ^{78}Ni region

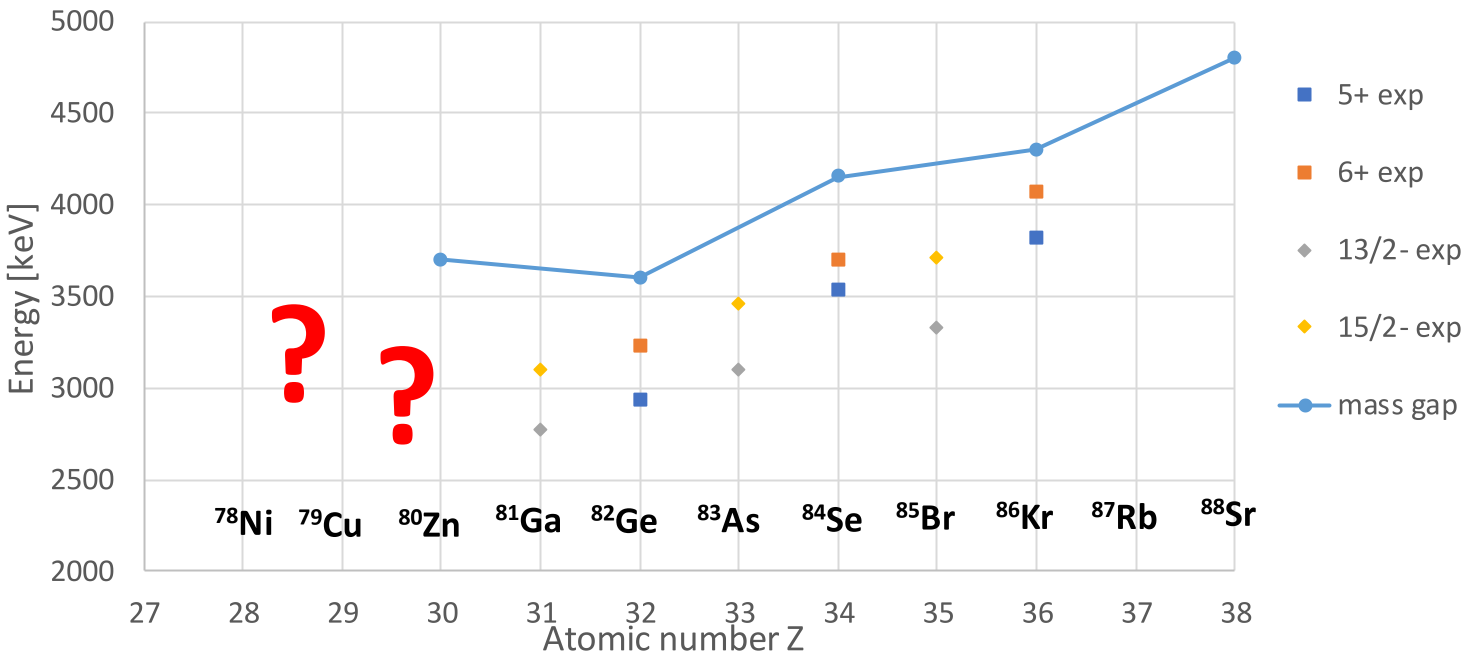




Quasi-SU(3) scheme: gds shells, similar case to N=20 with $f_{7/2}$-$p_{3/2}$

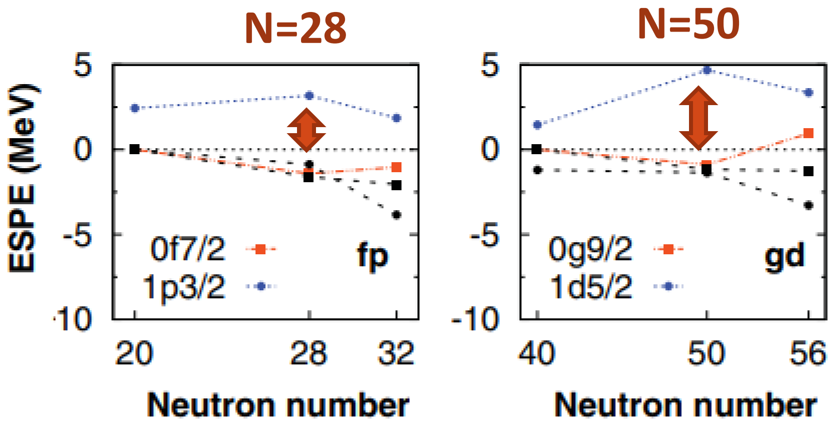
The N=50 shell gap

- **Mass gap**: from measured Sn values
- Quadratic behaviour of the shell gap
- **Spectroscopic gap**: from $5^+,6^+,7^+$ levels which are a $g_{9/2}$-$d_{5/2}$ N=50 core excitation



J. Hakala et al., Phys. Rev. Lett. 101, 052502 (2008)
S. Baruah et al., Phys. Rev. Lett. 101, 262501 (2008)
K. Heyde et al., Phys. Lett. B 176, 255 (1986).
T. Rzaca-Urban et al., Phys. Rev. C 76, 027302 (2007

<u>What is the origin of the «quadratic» behaviour of the N=50 gap ?
What components of the nuclear interaction can explain it ?</u>

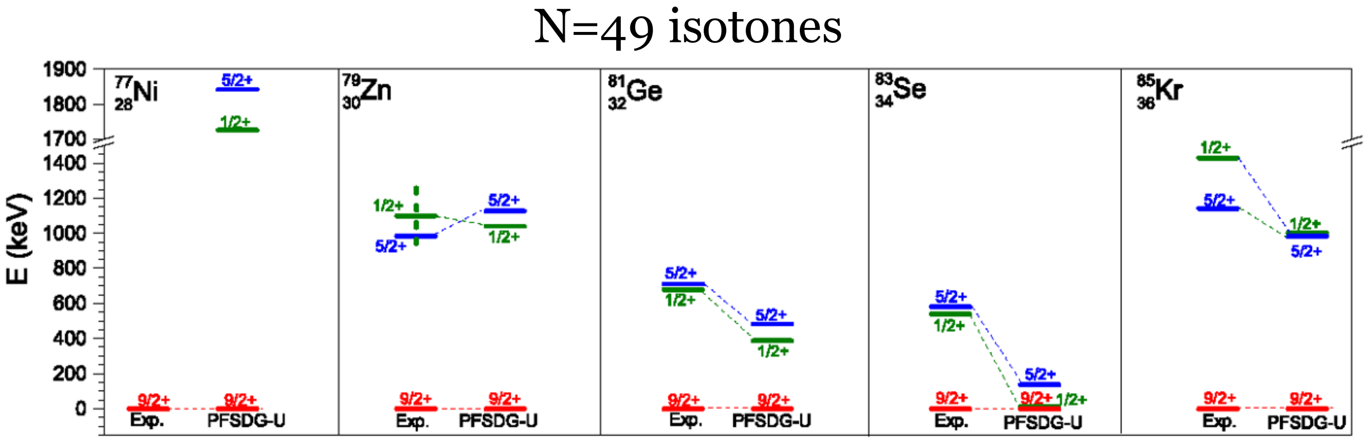


K. Sieja, F. Nowacki, Phys. Rev. C 85, 051301(R) (2012)

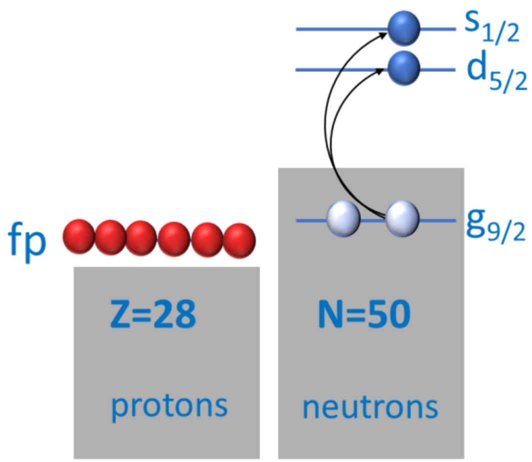
Realistic NN V_{lowk}
Empirical

Three-body force role in creating magic gaps

Shape coexistence around N=50



C. Wraith et al., Phys. Lett. B 771 (2017) 385391



many particle – many hole across N=50

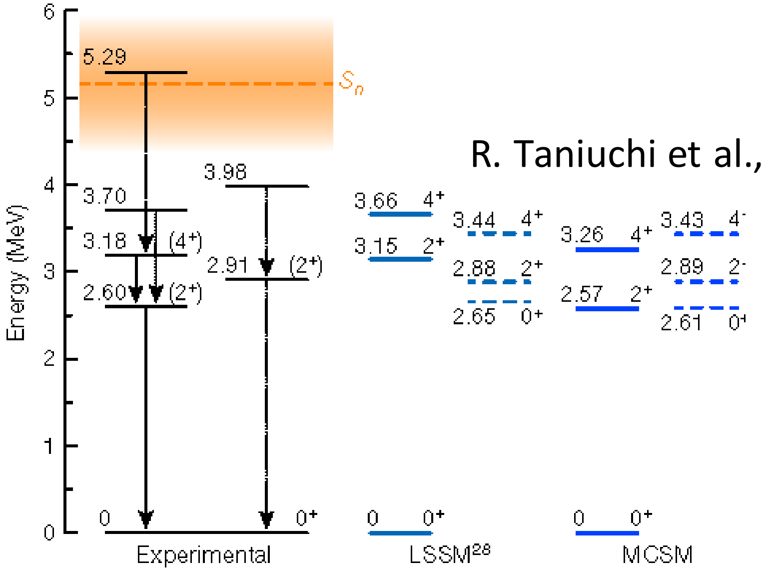
- Spherical gap :

energy cost ⬆

- Correlations by breaking the core:

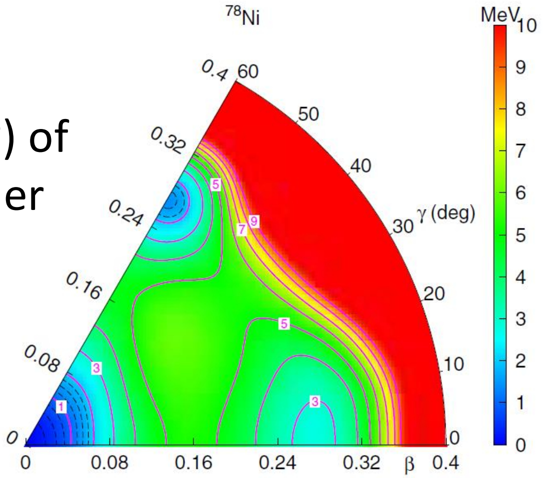
energy gain ⬇

- Lowering of energy from Z=36 to Z=32, then reincrease
- PFSDG-U shell-model interaction (by F. Nowacki)



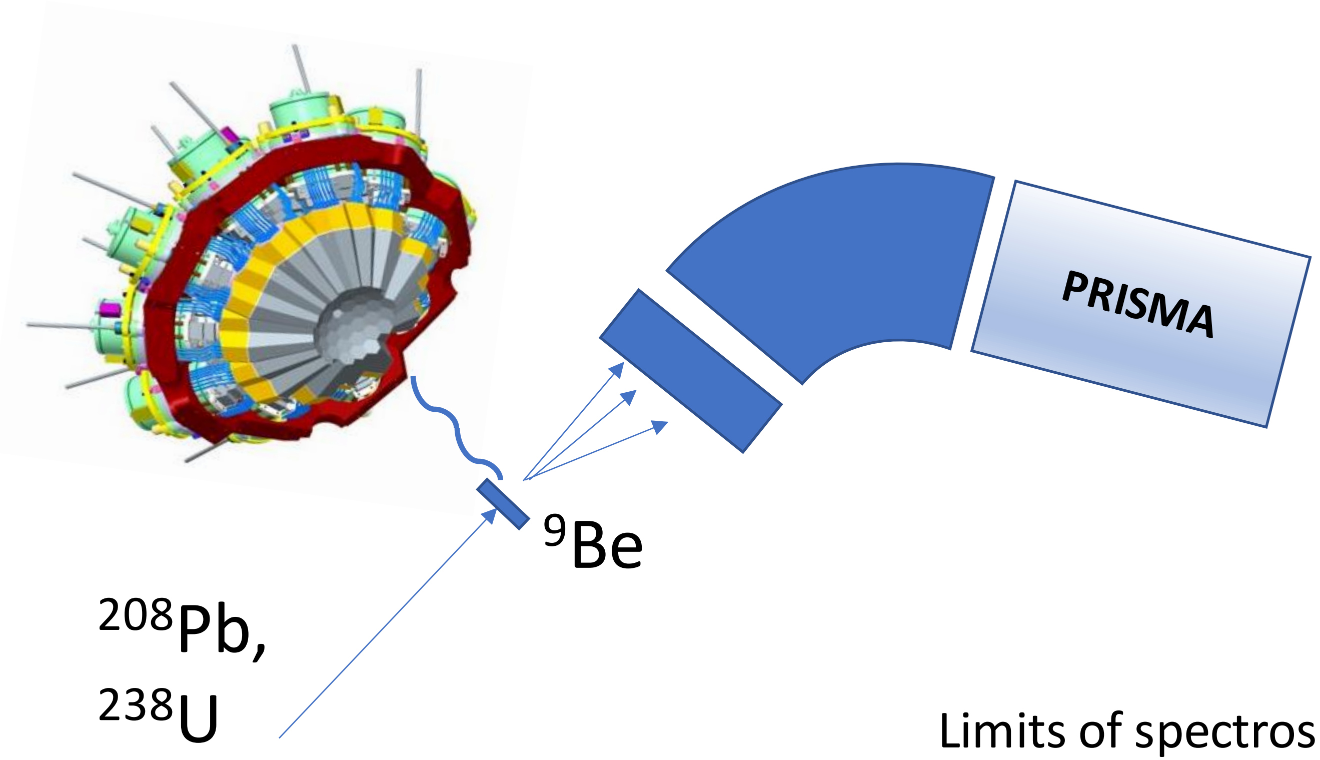
R. Taniuchi et al., Nature 569, 53–58 (2019)

Prediction (and observation ?) of a well deformed 4p-4h intruder structure in ^{78}Ni



F. Nowacki et al., Phys. Rev. Lett. 117, 272501 (2016)

^{208}Pb, ^{238}U + ^{9}Be fusion-fission reactions


PRISMA

^{9}Be

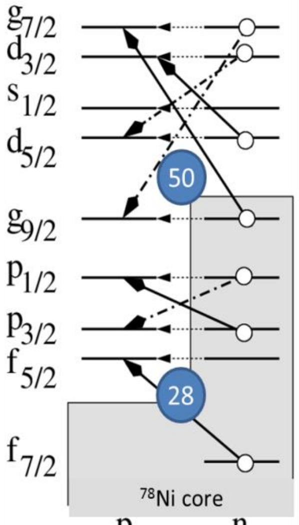
^{208}Pb,
^{238}U

- Fusion-fission reactions populate up to L=8-10
- few pnA of ^{208}Pb, ^{238}U @ 1300 MeV from PIAVE-ALPI
- Spectroscopy and lifetimes with plunger/DSAM

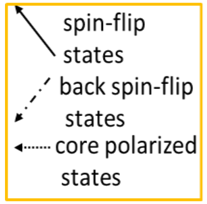
Limits of spectroscopy

	Ions/day in PRISMA	AGATA efficiency	γ-ray-ion / 14 days
^{80}Zn: 5^{+},6^{+}	5600	(1400 keV) 7%	1600
^{79}Cu: $9/2^{-}$	130	(3000 keV) 4%	40
^{79}Cu: $11/2^{-}$,$13/2^{-}$		(500) 12%	100

β decay for N=50 shell structure



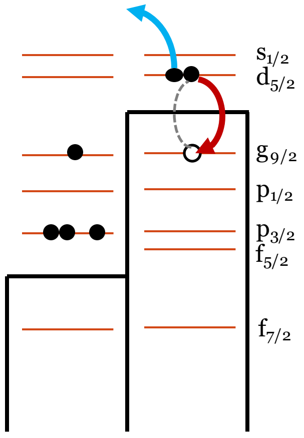
single(quasi)-particle GT transitions



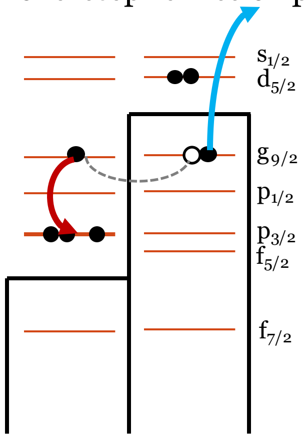
- GT decay breaks the N=50 core
- Large Q values (>10 MeV) in neutron-rich neuclei make GT decay possibile
- **B(GT)** (energy, strength) probes **theoretical models**

• Gamow-Teller doorway states

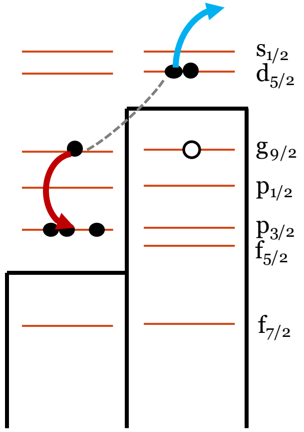
typical "one-step" emission processes



neutron-neutron particle-hole "collision"

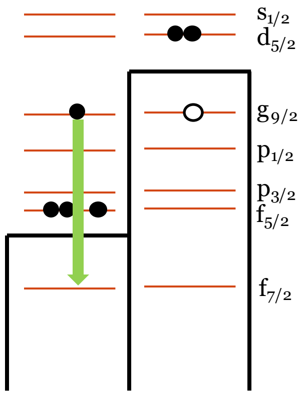


proton-neutron particle-hole "collision"



proton-neutron particle-particle "collision"

excited configuration after GT transition



E1 partners available

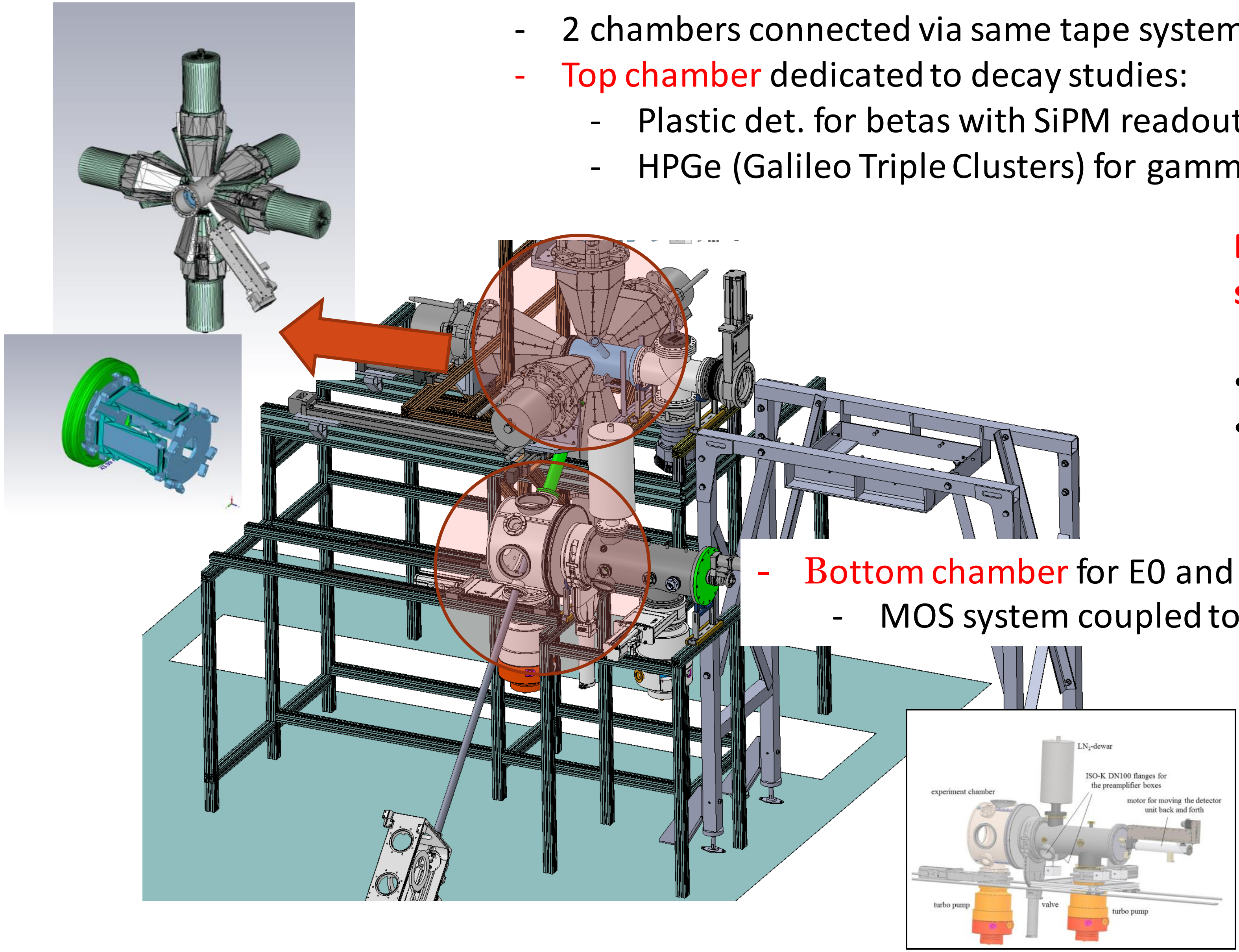
all involve high ℓ (ℓ ≥2) neutron transitions → inhibited

• SPES 1^{+} beams (> 10^{1} pps):

$^{78-80}$Cu, $^{78-82}$Zn, $^{80-87}$Ga, $^{80-87}$Ge, $^{82-89}$As, $^{94-102}$Rb

β-delayed spectroscopy – G. Benzoni

- 2 chambers connected via same tape system
- Top chamber dedicated to decay studies:
  - Plastic det. for betas with SiPM readout
  - HPGe (Galileo Triple Clusters) for gamma rays



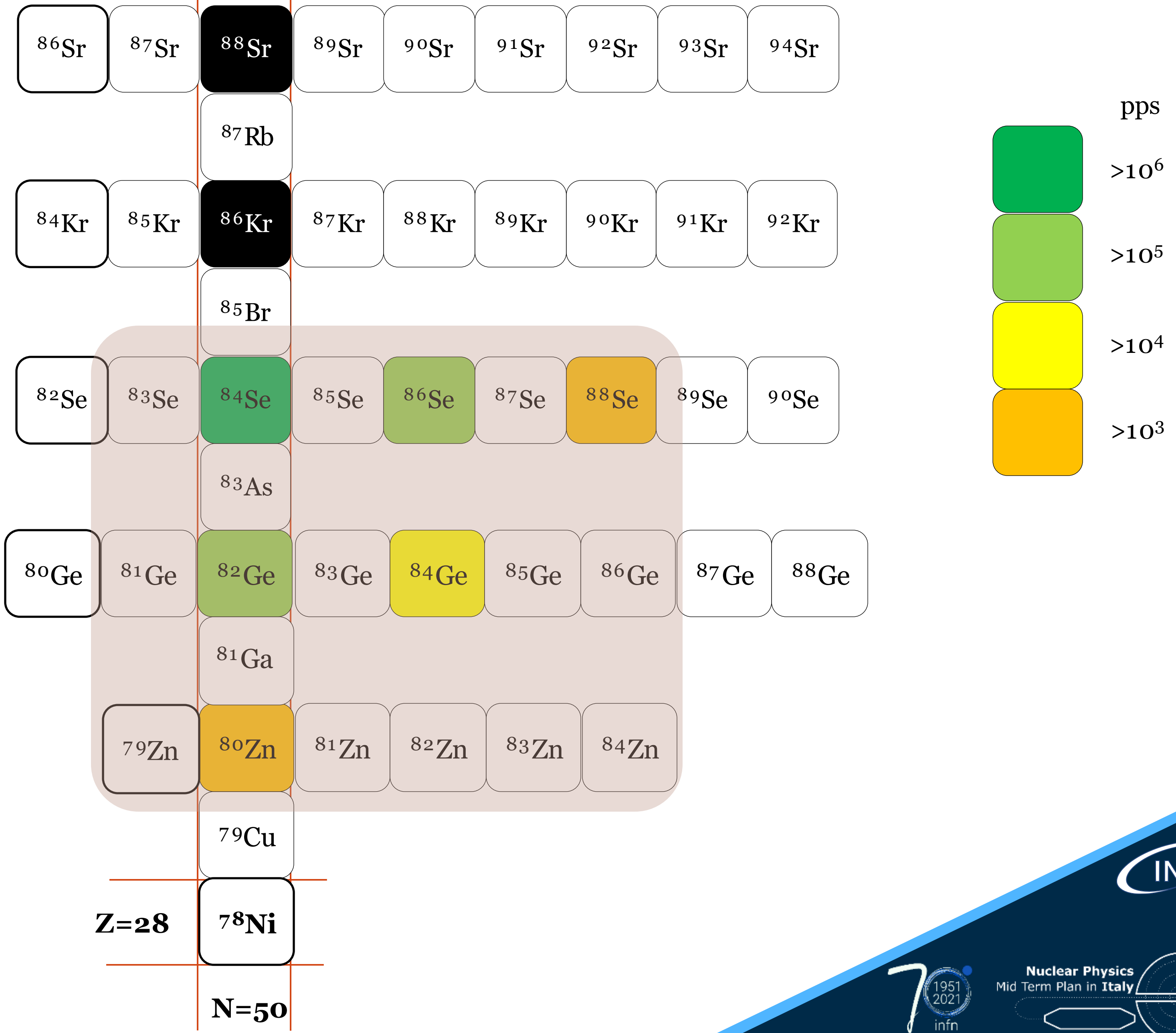
Detector for β-delayed neutron spectroscopy:

- TOF detector (Vandle, Monster…)
- CLYC scintillators for direct neutron energy spectroscopy

- Bottom chamber for E0 and EC measurements:
  - MOS system coupled to cooled Si(Li)

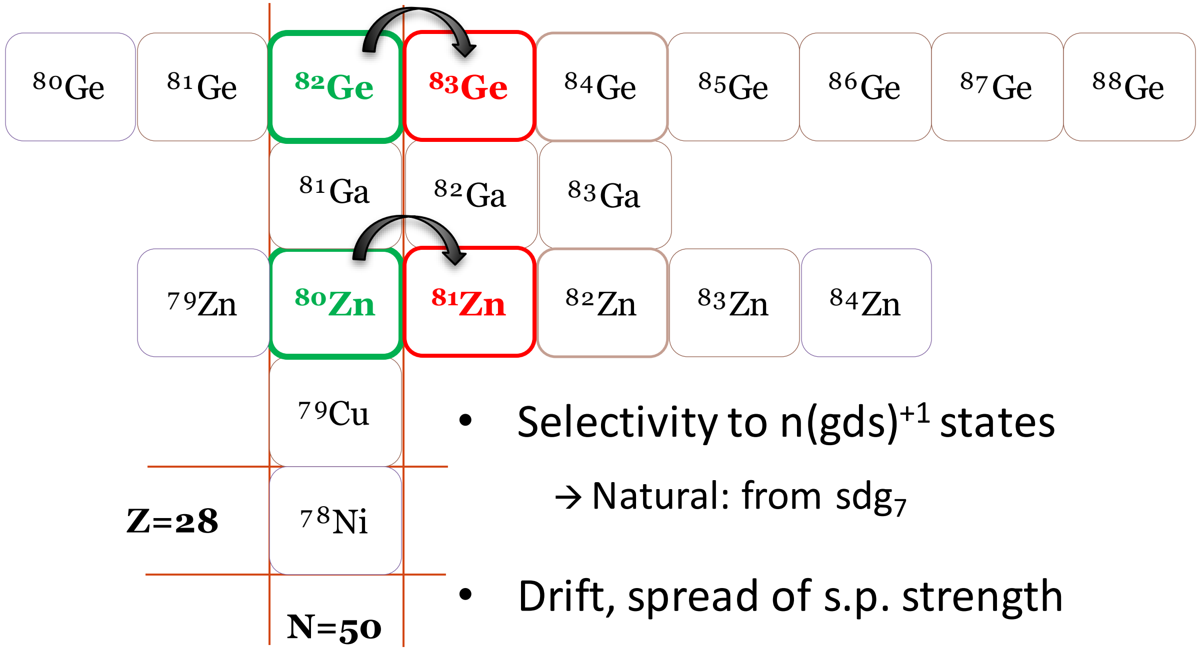
INFN Milano, Firenze, Perugia, Uni. Camerino

Direct Transfer reactions around N=50

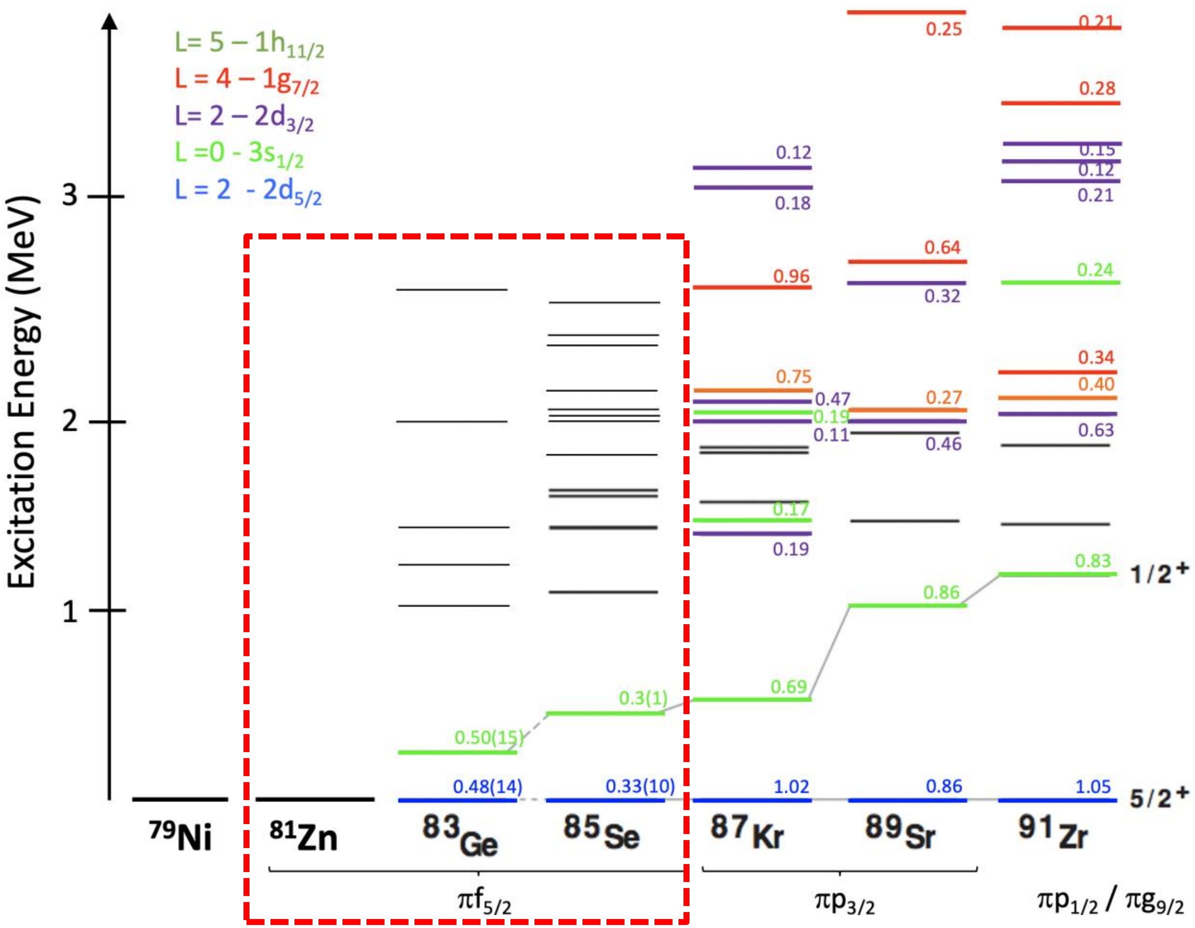


- N=50 – s.p. structure evolution
- Lifetimes after transfer reactions

Shell evolution: Neutron Addition at/around N=50

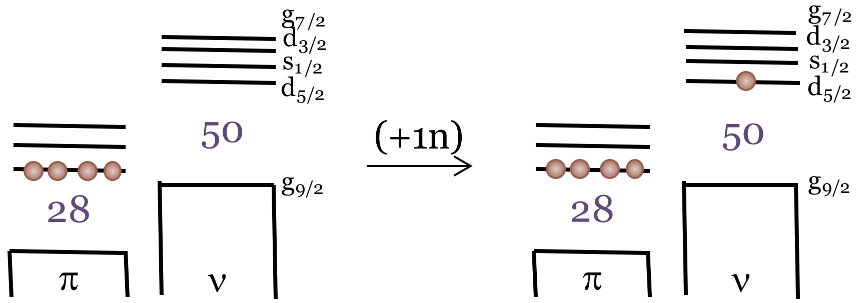


- Selectivity to n(gds)$^{+1}$ states
  - → Natural: from sdg$_7$
- Drift, spread of s.p. strength
  - → Cross sections -> s.p. strength



Studies enabled by new SPES beams

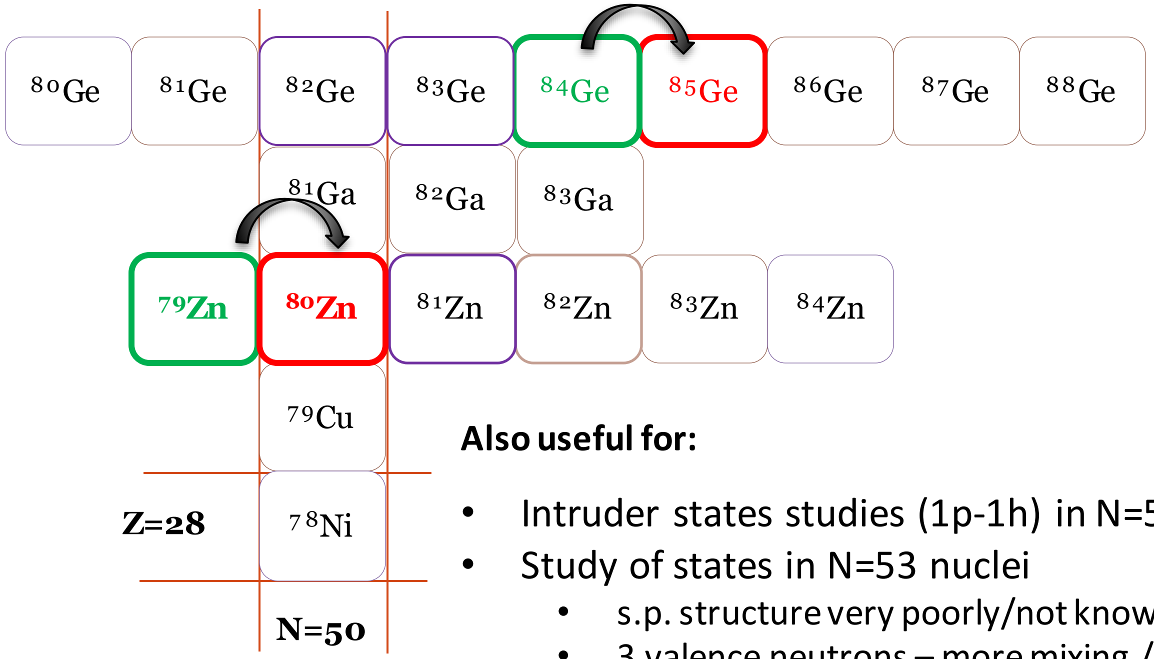
Neutron addition on N=50 : ^{82}Ge, ^{80}Zn(d,p)



^{82}Ge (gs)

^{83}Ge: sp. states
(5/2+,3/2+,7/2+)

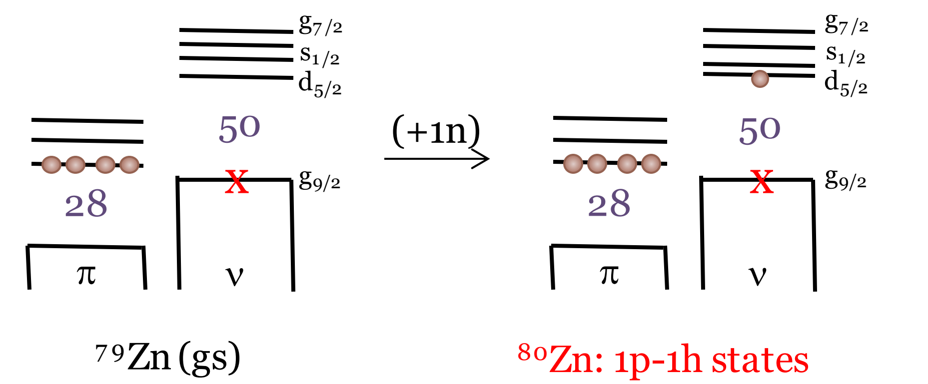
Other possibilities around N=50



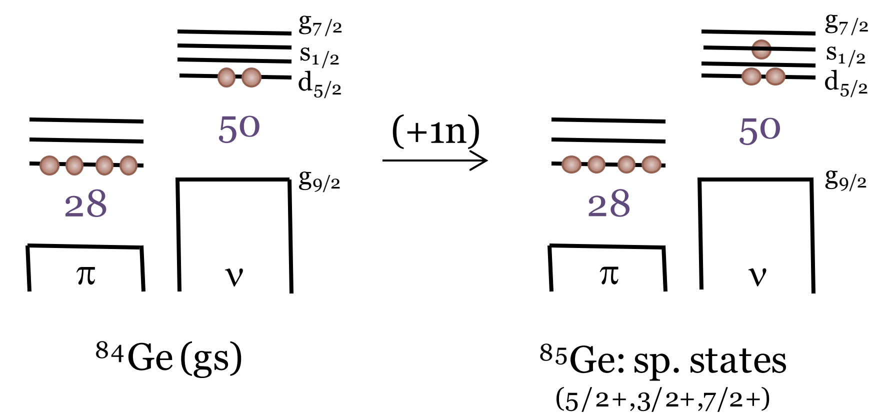
Also useful for:

- Intruder states studies (1p-1h) in N=50 nuclei
- Study of states in N=53 nuclei
  - s.p. structure very poorly/not known
  - 3 valence neutrons – more mixing /collectivity

Intruders: n addition N=49 : ^{81}Ge, ^{79}Zn(d,p)



Neutron addition on N=51,52 : ^{83,84}Ge, ^{86}Se(d,p)



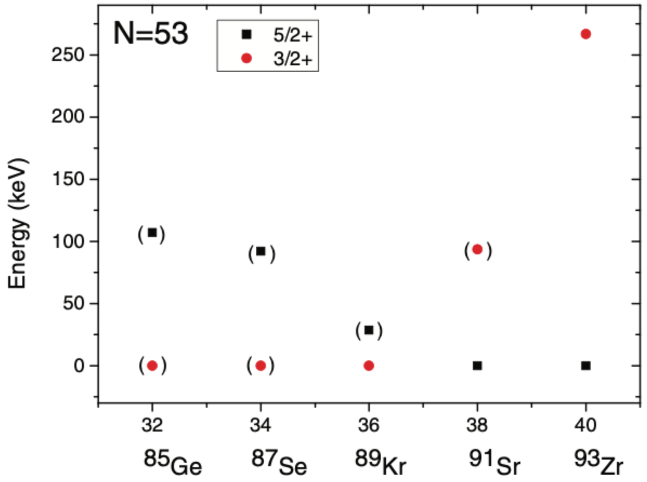


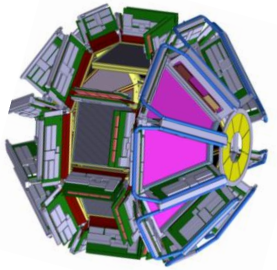
FIG. 4. (Color online) Systematics of the first $5/2^+$ and $3/2^+$

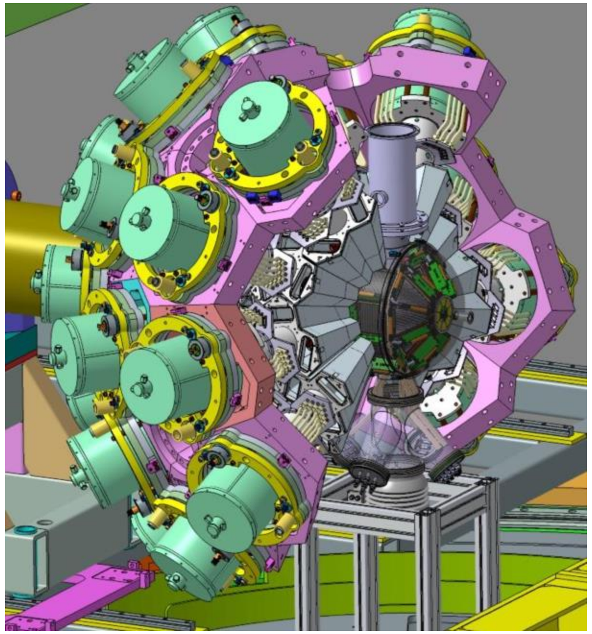
A. Korgul et al., PRC88, 044330 (2013)

Transfer reaction studies: tools and technique

GRIT + AGATA setup

GRIT
4π Si array

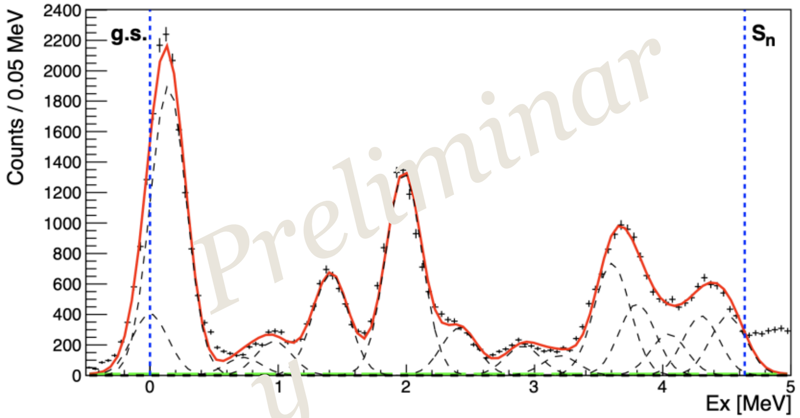


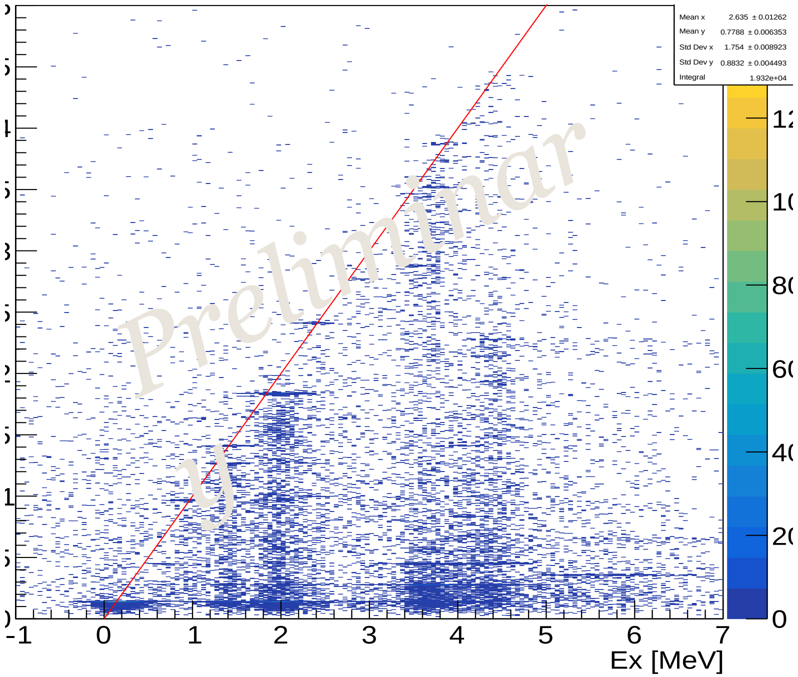


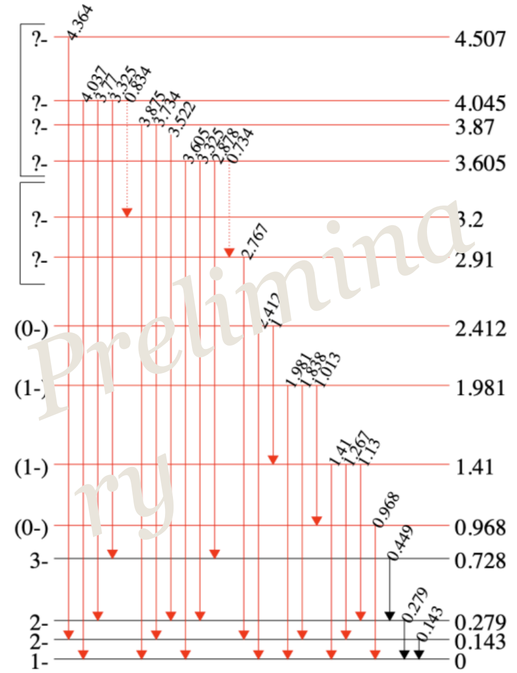
- High efficiency for particles and γ-rays
  (many reactions channels meas. simultaneously)
- High granularity (strip pitch < 1 mm)
- Large dynamical range
- Special targets (Cooled ^{3,4}He cell, pure H, tritium)
- PID using Pulse Shape Analysis techniques
- New Integrated electronics

Illustration of p-γ capabilities

- Study of **odd-odd ^{48}K** from ^{47}K(d,p)
- **High density** of states
- Courtesy of **C. Paxman (Univ. of Surrey)**
- GRIT prototype
  (MUGAST) + AGATA @ GANIL







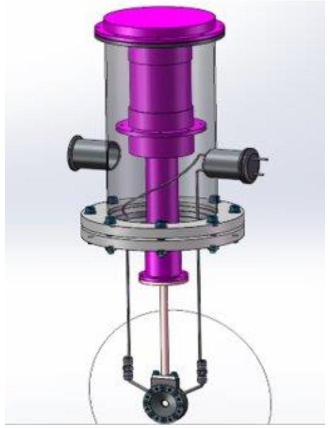
Cryogenic targtes

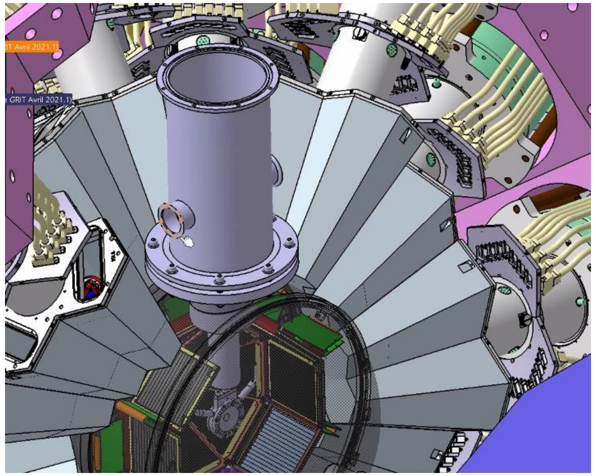
Cryogenic ^{1,2}H, ^{3,4}He targets

PRIN

CTADIR

- PRIN2017 call, 770 k€
- 3.8 -2 μm HAVAR windows
- GM cryocooler for horizont al use
- 3 K guaranteed in the head
- Design: finished
- Construction: finished
- Gas filling system in 2022
- Test in Autumn 2022 at CN
- ^{3,4}He 1-2 mg/cm^2





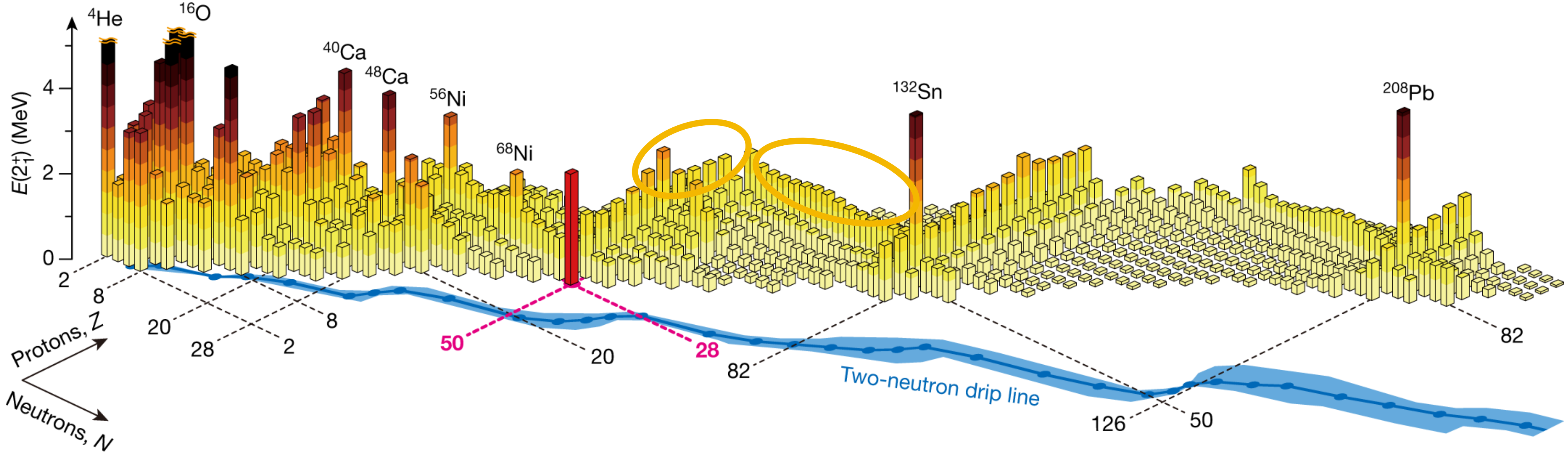
Cryogenic semisolid ^{1,2}H target

CHyMENE (CEA Saclay)

A. Gilibert et al., Eur. Phys. J. A (2012) 49: 155

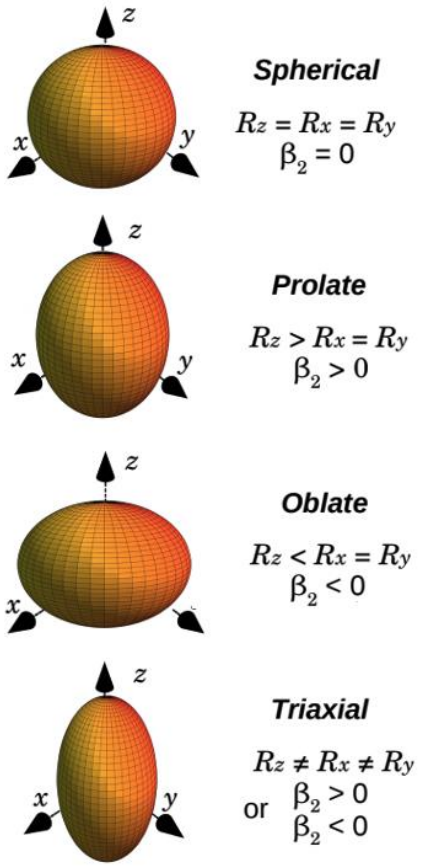
- Study for integration with AGATA- GRIT
- ^{1,2}H 0.1-0.5 mg/cm^2

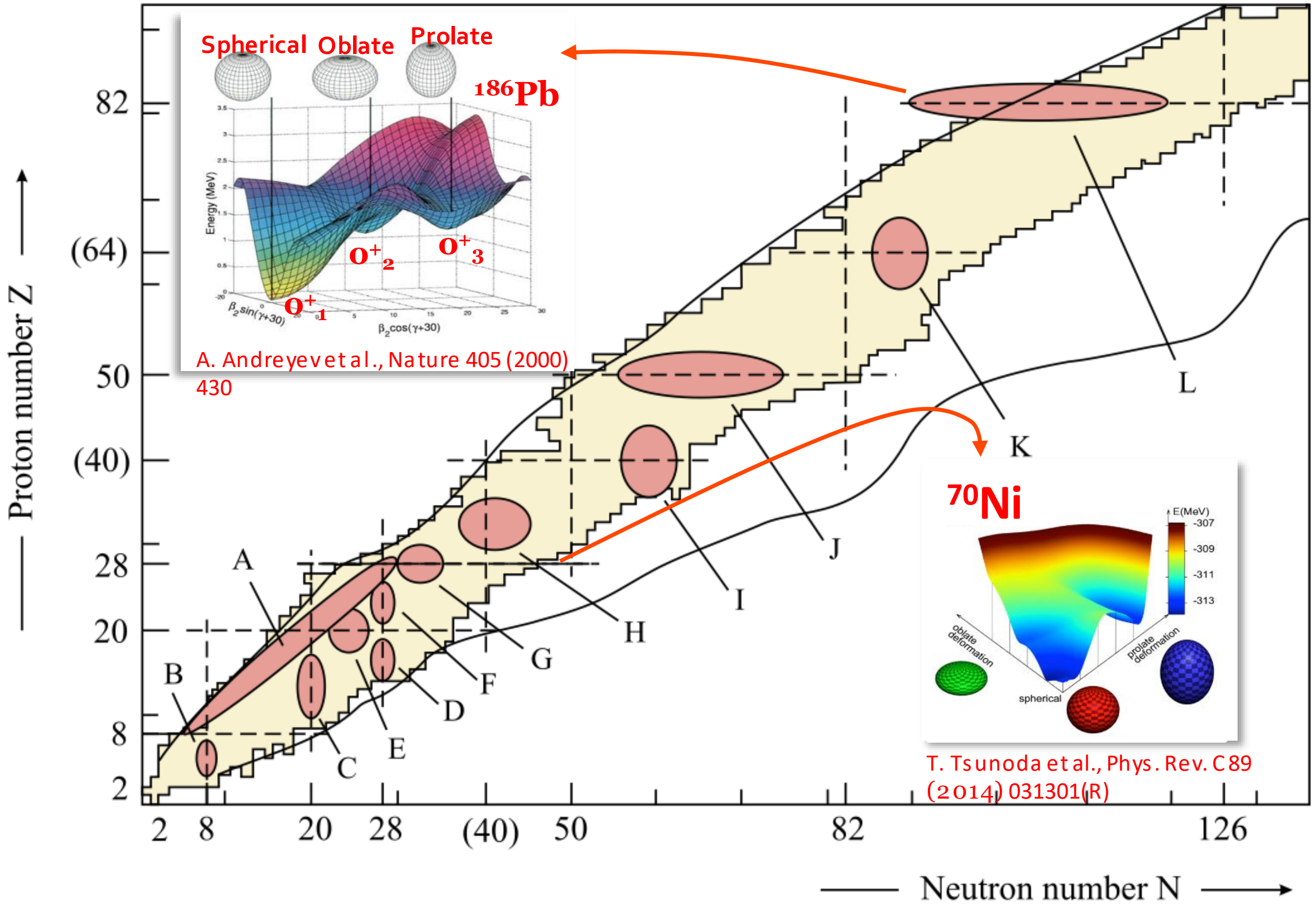
From ^{78}Ni to ^{132}Sn



Shape coexistence

Nuclear shape coexistence is the phenomenon in which **distinct shapes** occur within the same nucleus and at a **similar energy**





A. Andreyev et al., Nature 405 (2000) 430

T. Tsunoda et al., Phys. Rev. C 89 (2014) 031301(R)

Kris Heyde and John L. Wood, *Rev. Mod. Phys.* 83 (2011) 4

A → L: regions of the nuclear chart in which shape coexistence has been observed

β-delayed e$^-$ (E0) spectroscopy for ^{96}Sr

$$\rho^2(E0) = \frac{Z^2}{R^4} a^2 b^2 \left(\Delta \langle r^2 \rangle\right)^2$$

Wave function mixing

Difference in mean square radii

Structure above the ^{96}Sr THIRD 0$^+$ state

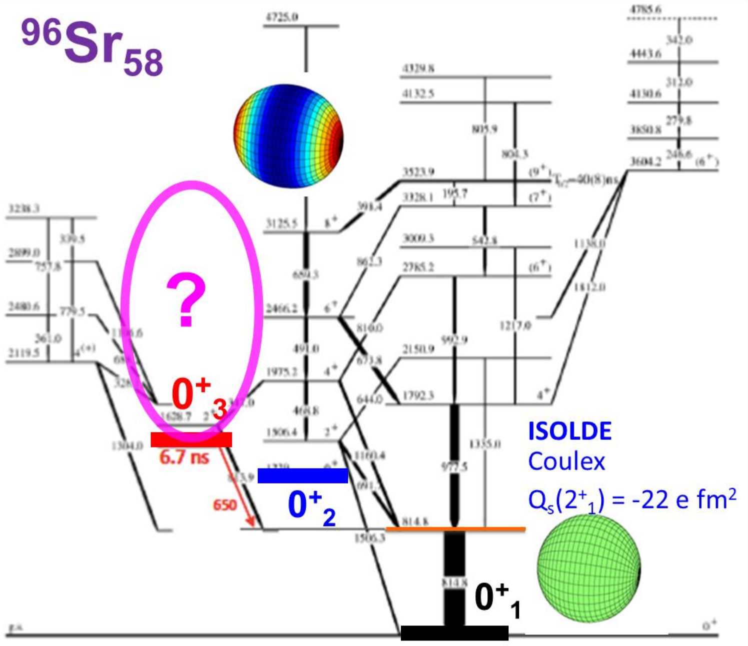
1) $0^+_3 \rightarrow 2^+_2$ decay by

very retarded E2

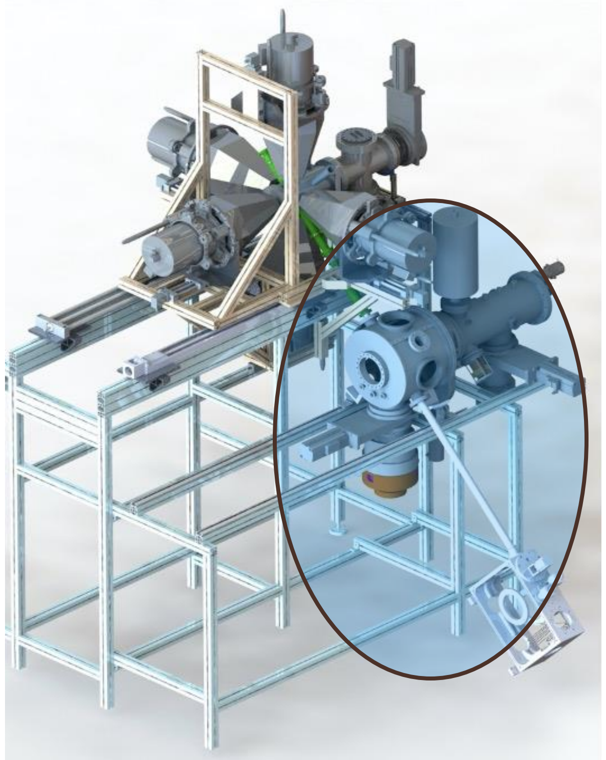
2) 0^+_3 state may be correspond to a THIRD minimum associated to another shape
→ NOT predicted by HFB Theory

Other LOIs:

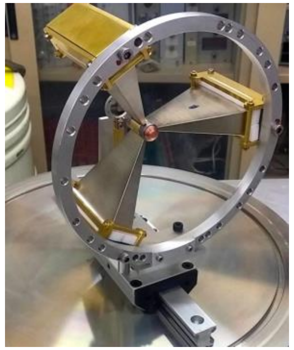
LOI SPES: ^{96,97}Y (L. Iskra, S. Leoni)
LOI SPES: ^{96}Sr (S. Leoni, B. Fornal)



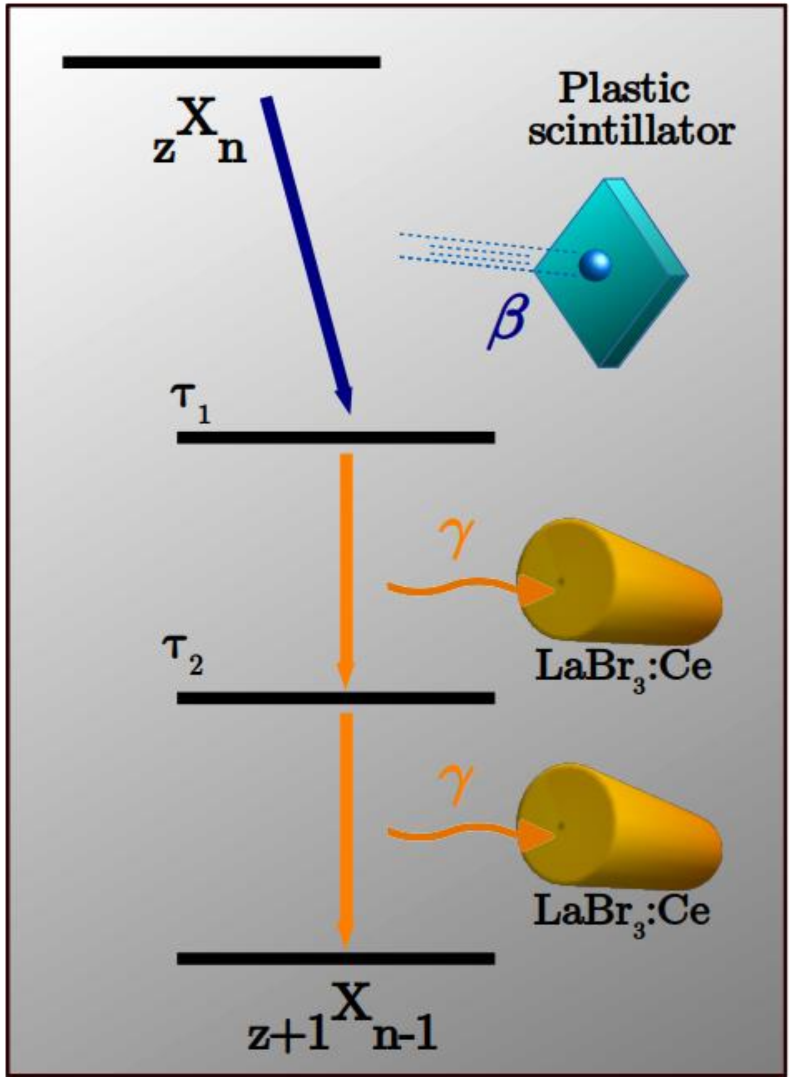
SLICES at the β-decay station of SPES



^{96}Rb yield 2.5 x 10^7 pps [SPES Phase 1 (I_p=5μA and UCx target)]



Lifetimes from β decay

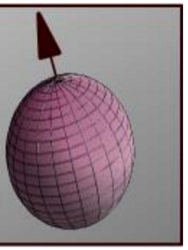


- Lifetime measurements using fast scintillators
- Access to ps - tens of ns lifetime range
- Extra selectivity thanks to β radiation detection

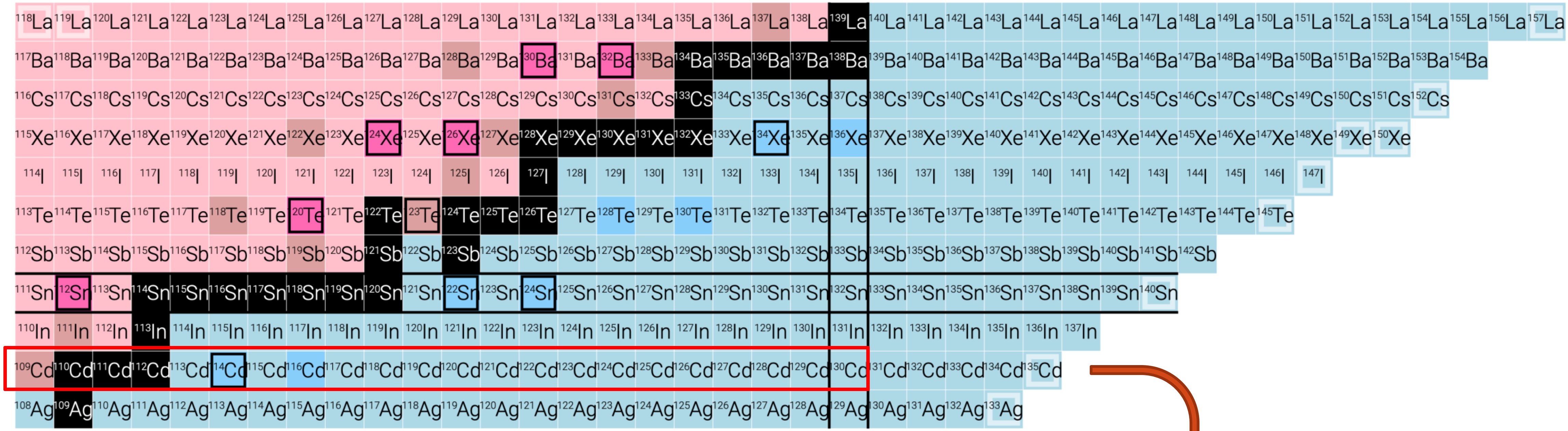
Coincidences:

$\beta - \gamma$	τ_1
$\beta - \gamma - \gamma$	τ_2 (β-tag)
$\gamma - \gamma$	τ_2

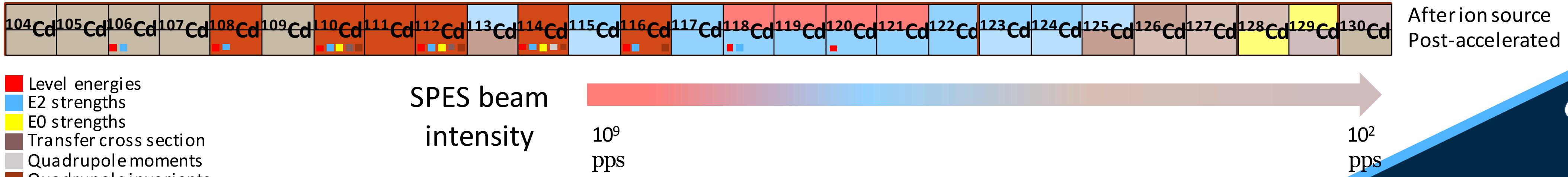
Reduced transition probabilities	B(E2)
Electric quadrupole moments	Q0
Deformation parameter	β



SPES will open the possibility of investigating shape coexistence in new regions, where new orbitals become active
In particular around Kr, Zr, Mo, Pd and Cd isotopes around mass A=100



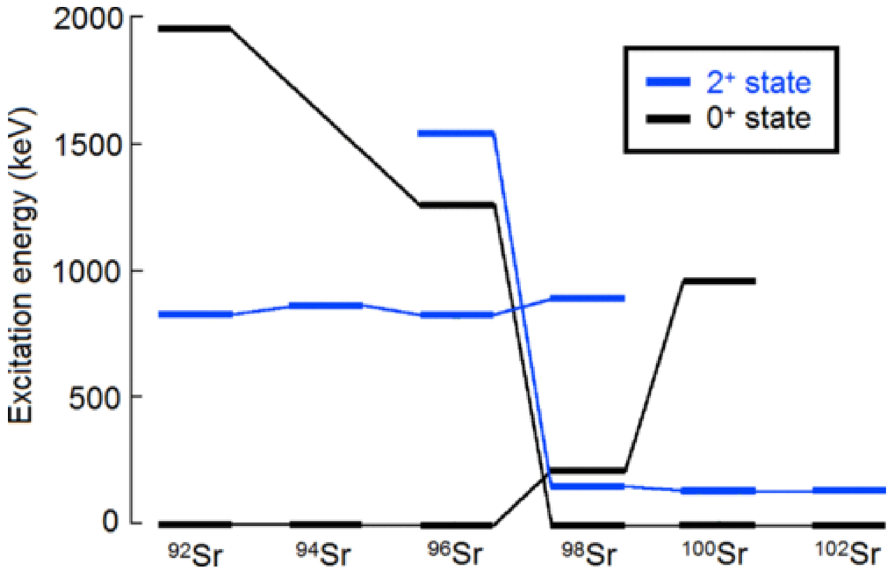
Example: Cd isotopic chain



- 🟥 Level energies
- 🟦 E2 strengths
- 🟨 E0 strengths
- ▨ Transfer cross section
- ▨ Quadrupole moments
- ▨ Quadrupole invariants

P.E. Garrett, M. Zielińska and E. Clément, *Progress in Particle and Nuclear Physics* 124 (2022) 103931

Direct reactions for shape coexistence/transition around N=60

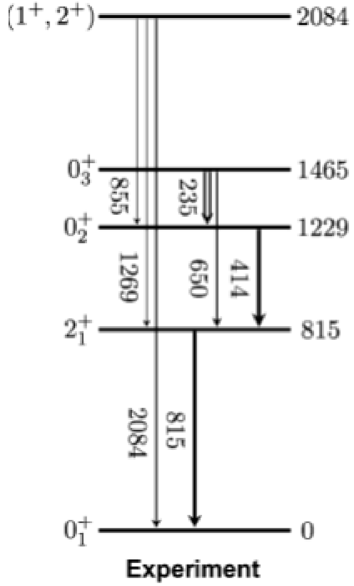


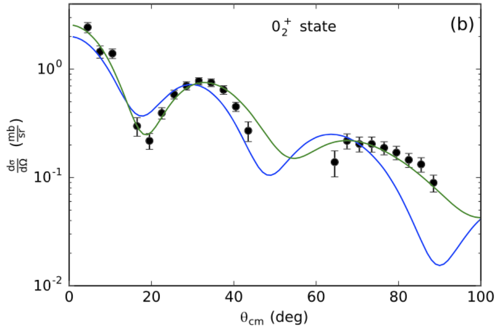
- Study of shape transition from a **single-particle perspective**
- **Microscopic nature** of coexisting 0^+, 2^+ states
- Many **unexpected observations** compared to SM prediction
- Several beams very well produced at SPES in the region (^{94,95,96}Kr,^{96,97,98}Sr)

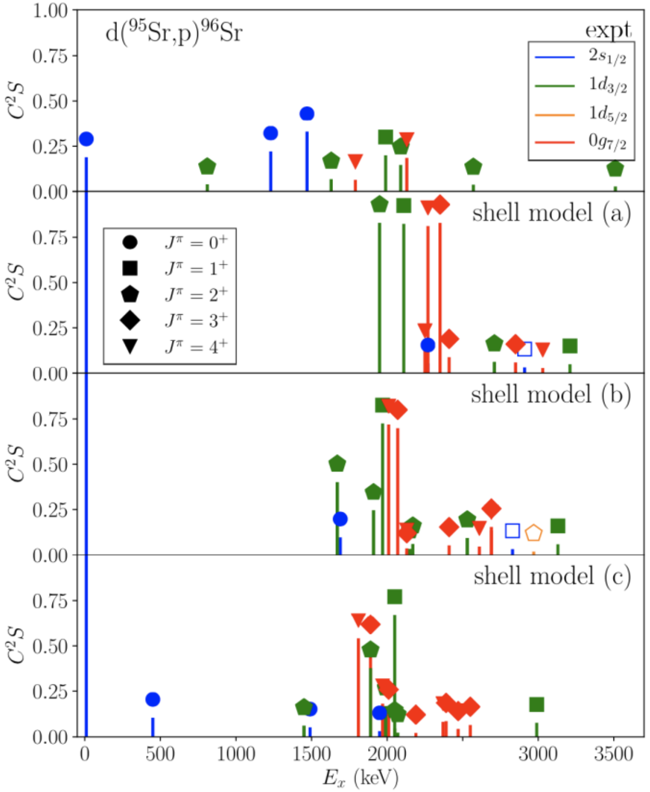
→ allow **precise studies** with part.-γ coincidences

^{94,95,96}Sr(d,p)^{95,96,97}Sr – S. Cruz et al.

ν($s_{1/2}$) transfer on ½+ gs of ^{95}Sr





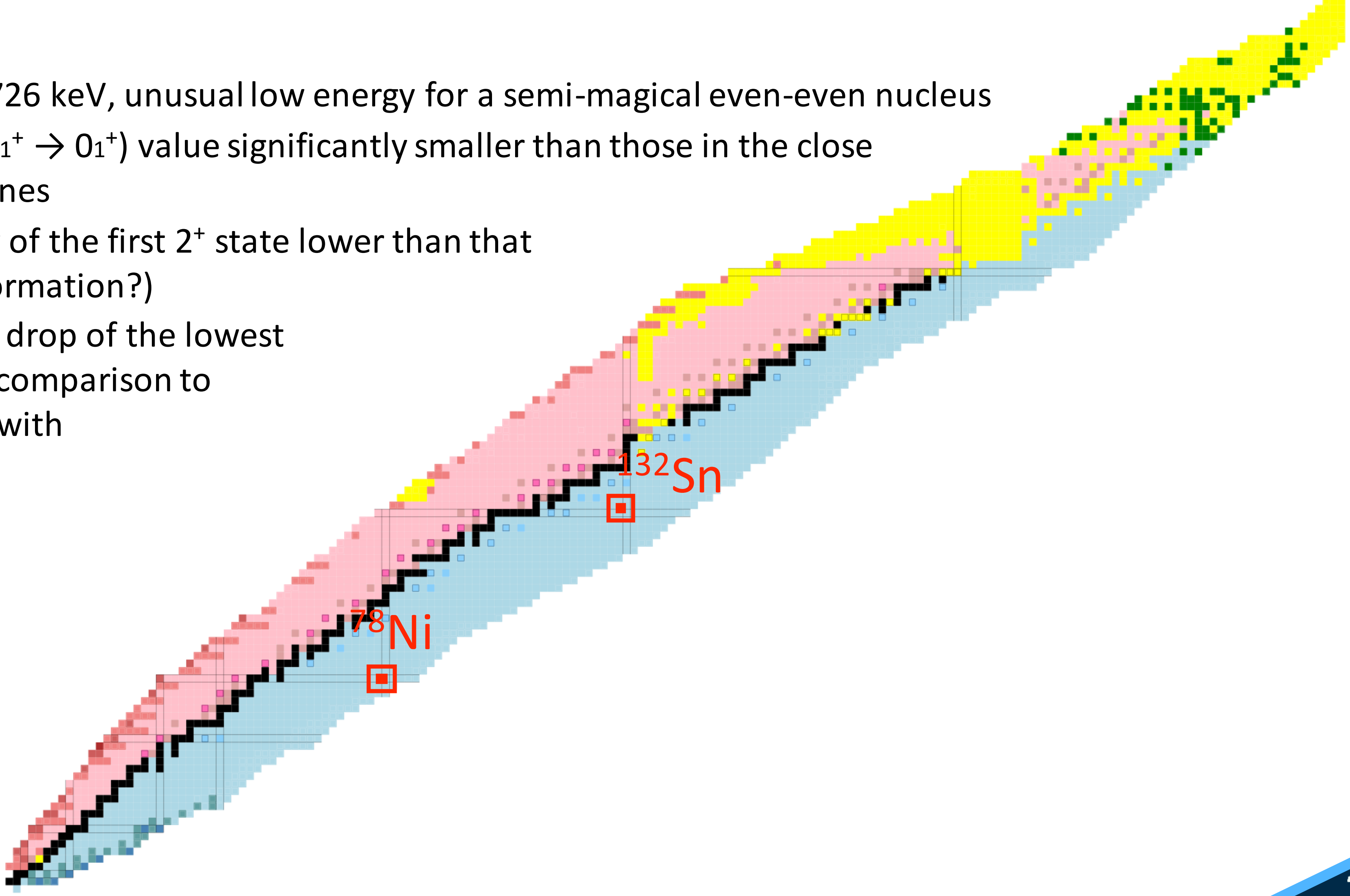


S. Cruz et al., PRC100, 054321 (2019)

S. Cruz et al., PLB786, 94 (2018)

Low-Energy Coulomb Excitation

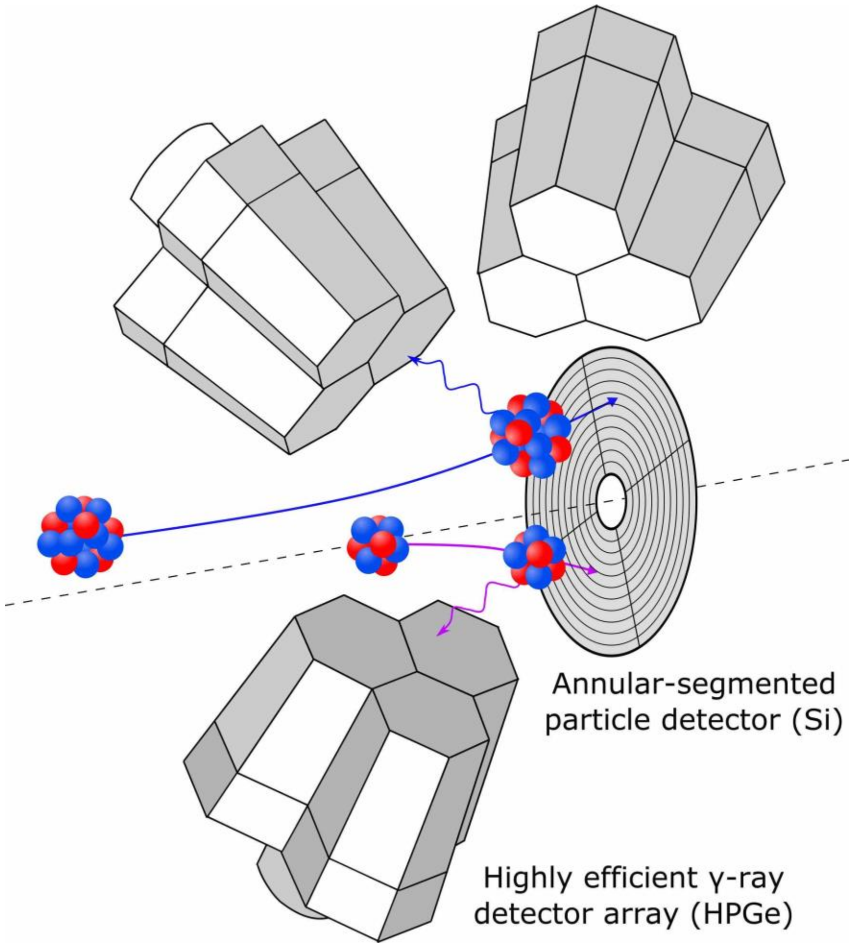
- ^{134}Sn: 2_1^+ at 726 keV, unusual low energy for a semi-magical even-even nucleus
- ^{136}Te: B(E2; $2_1^+ \rightarrow 0_1^+$) value significantly smaller than those in the close heavier isotones
- ^{128}Cd: Energy of the first 2^+ state lower than that in ^{126}Cd (deformation?)
- ^{135}Sb: Energy drop of the lowest $5/2^+$ state in comparison to the isotopes with $N \leq 82$



Low-Energy Coulomb Excitation

- Available intensities and energies at SPES suitable for low-energy Coulomb excitation (first-day technique at other ISOL RIB facilities)
- Clean spectra, population from the ground state
- Access to B(E2), B(E3) values and spectroscopic quadrupole moments Q_s of excited states
- In favorable conditions, direct access to the shape (β_2 and γ Hill-Wheeler parameters) through quadrupole sum rules

Ideal technique to investigate emerging or vanishing deformation due to shell evolution



GOSIA calculations – M. Rocchini

- Beams at the safe energy on ^{208}Pb target 1-mg/cm^2 thick
- ε_γ = 4% at 1332.5 keV, particle detection at forward angles (30 - 80 deg)
- Expected SPES (post-accelerated) intensities
- B(E2) values from systematics or shell-model calculations

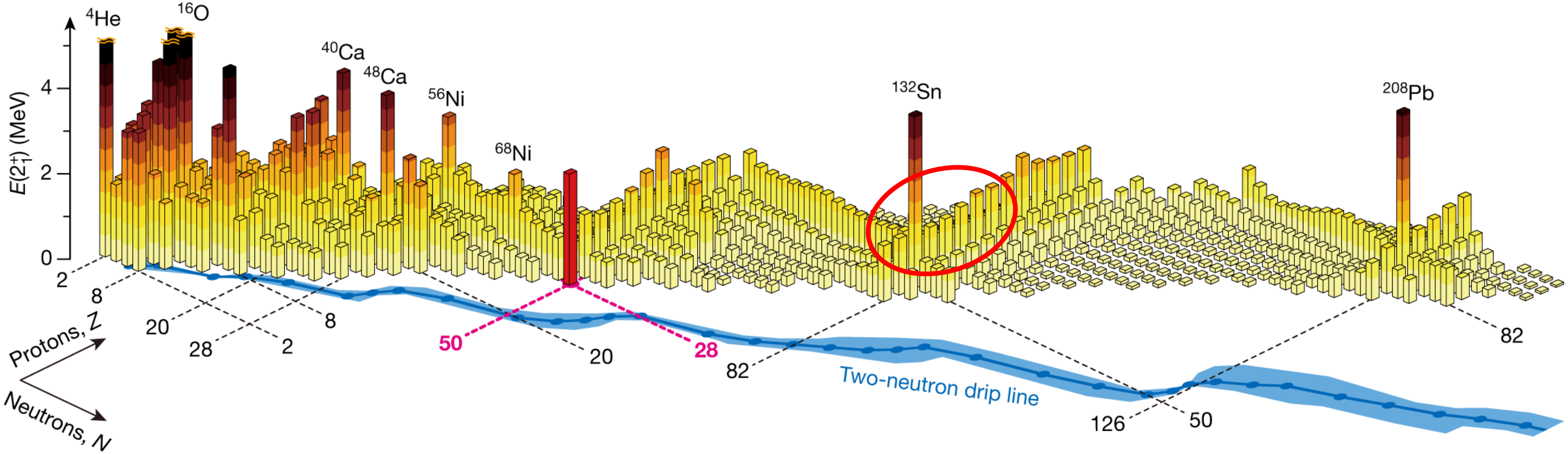
Nucleus	Transitions	γ Energy [keV]	Counts/h
^{126}Cd	$2^+ \rightarrow 0^+$	652	1000
	$4^+ \rightarrow 2^+$	815	90
^{137}I	$11/2^+ \rightarrow 7/2^+$	621	300
	$9/2^+ \rightarrow 7/2^+$	554	30
^{134}Sn	$2^+ \rightarrow 0^+$	726	20

Nucleus	Transitions	γ Energy [keV]	Counts/h
^{125}Sb	$5/2^+ \rightarrow 7/2^+$	282	84
	$3/2^+ \rightarrow 5/2^+$	158	51
	$3/2^+ \rightarrow 7/2^+$	440	34
	$1/2^+ \rightarrow 5/2^+$	241	0.15
	$11/2^+ \rightarrow 7/2^+$	707	191
	$9/2^+ \rightarrow 7/2^+$	798	57

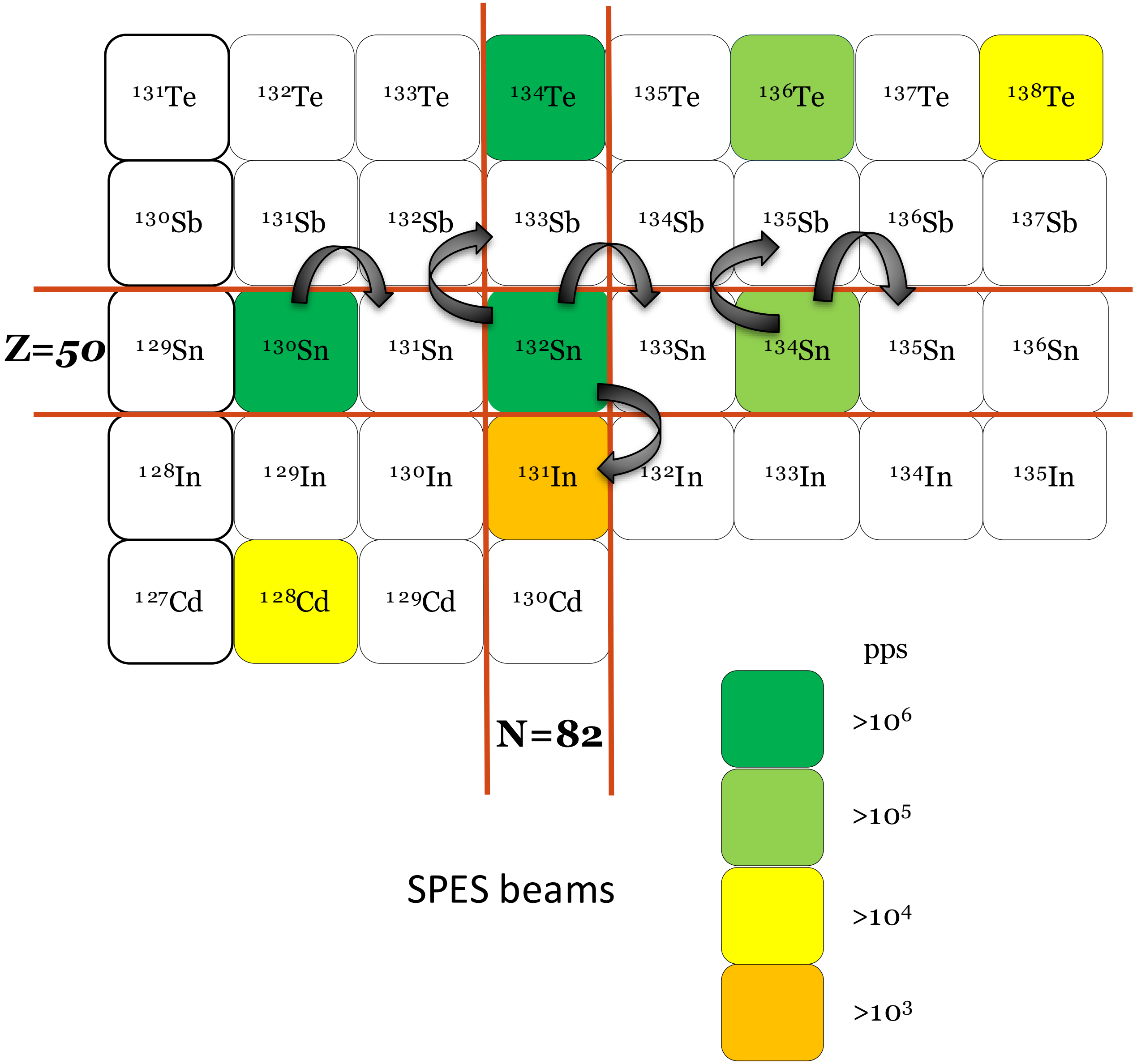
LOI SPES: *^{96,97}Y (L. Iskra, S. Leoni)*

LOI SPES: *^{96}Sr (S. Leoni, B. Fornal)*

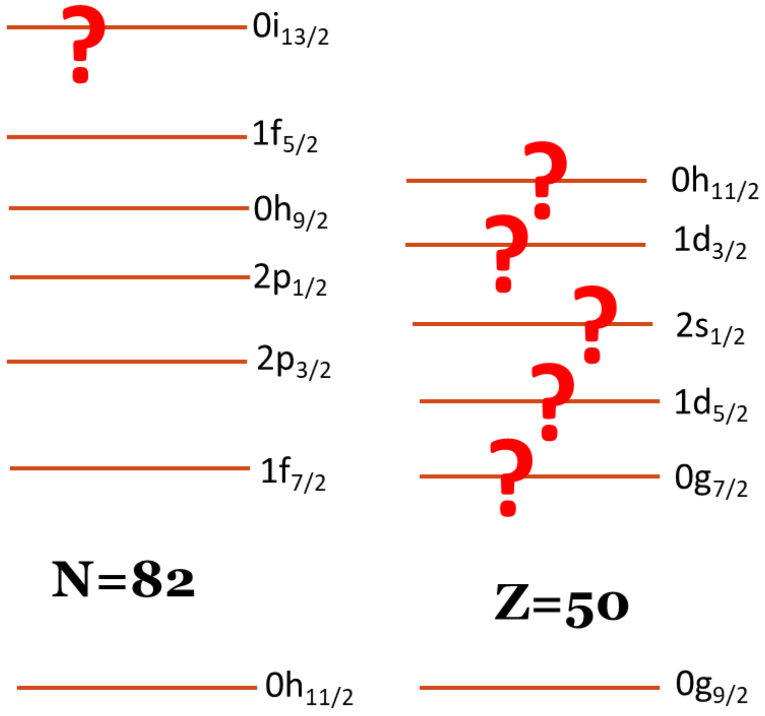
The region around ^{132}Sn



The region around ^{132}Sn



SPES beams



- Poor knowledge of shell structure for both protons and neutrons
- Theoretical ab-initio calculations start to become available

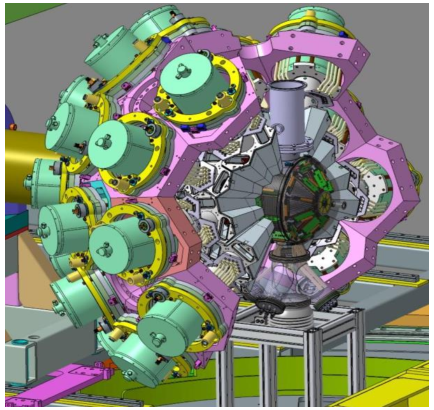
Direct transfer for large-ℓ shells

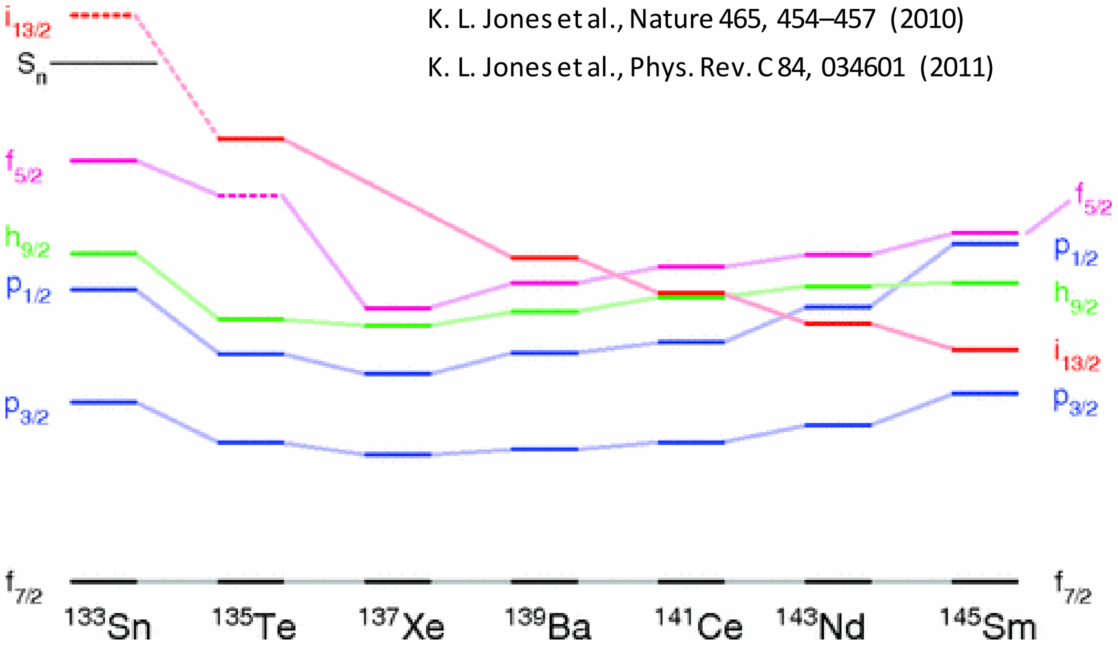
- Neutron shells: **(d,p); (d,t) reactions** with **$^{126-134}$Sn** beams at 10 MeV/u BUT: large-ℓ shells (ℓ=5, ℓ=6) implies low cross sections

D. Mengoni et al.

(^{4}He,^{3}He) with CTADIR
(^{13}C,^{12}C); (^{9}Be,^{8}Be) for lifetimes

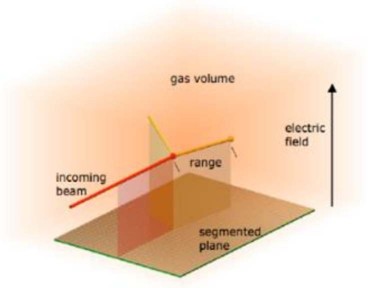
Population or large ℓ shells





K. L. Jones et al., Nature 465, 454–457 (2010)
K. L. Jones et al., Phys. Rev. C 84, 034601 (2011)

- Proton shells: **(^{3}He,d); (t,^{4}He) reactions** with **$^{126-134}$Sn** beams at 10 MeV/u



- <u>Use of an active target (TPC also possible)</u>

Lifetimes after direct transfer reactions

- Plunger or DSAM techniques after (d,p), (d,t) reactions
- How collective are the states populated by the transfer reaction ?

One wave function
$|\psi>$

$<\psi\ ||er^2||\psi>$
Electromagnetic matrix element

$<\psi\ ||a^\dagger||\psi>$
Nucleon addition/removal

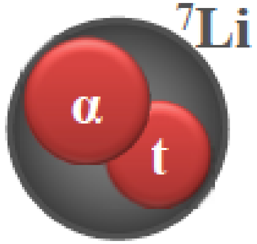
Two observables at the same time

Possible reactions:

- Beam intensity >10^5 pps
- GRIT+AGATA+plunger
- ^{130,132}Sn(d,p)^{131,133}Sn
- ^{80,82}Ge(d,p)^{81,83}Ge, ^{84}Se(d,p)^{85}Se

Cluster Transfer Reactions

$$^{A}X + {}^{7}Li \rightarrow (^{A}X + t) + \alpha$$
$$\rightarrow (^{A}X + \alpha) + t$$



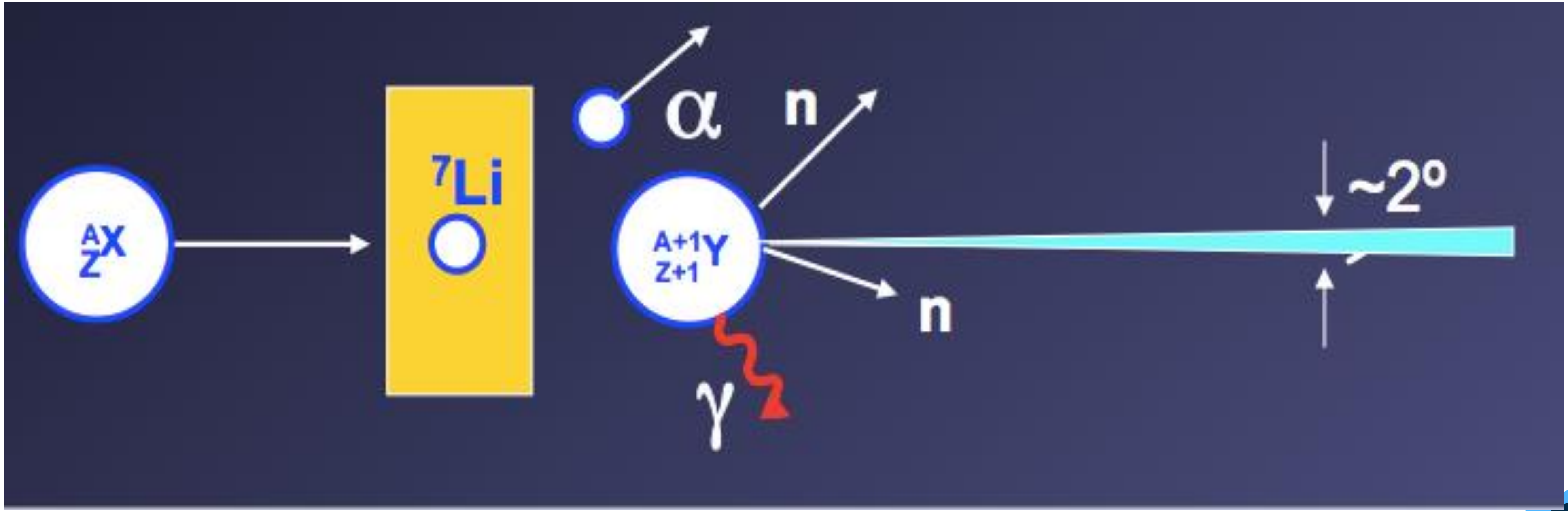
Weakly Bound Target
B.E.(α-t) = 2.5 MeV

Cluster Structure

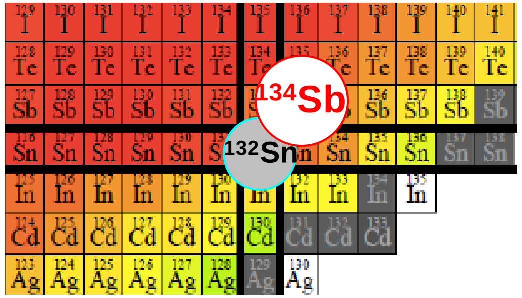
- *Inverse Kinematics, few MeV/A*
- *Transfer of* **t or α**
- *Evaporation of few neutrons*
- ***Population of medium-spins and excited states***

- *Clean Tagging on emitted particle*
- *Very Forward Focused*
- *No need for recoil detection for Doppler correction*

N. Cieplicka, S. Leoni, B. Fornal



MULTIPLETS of valence nucleons around ^{132}Sn

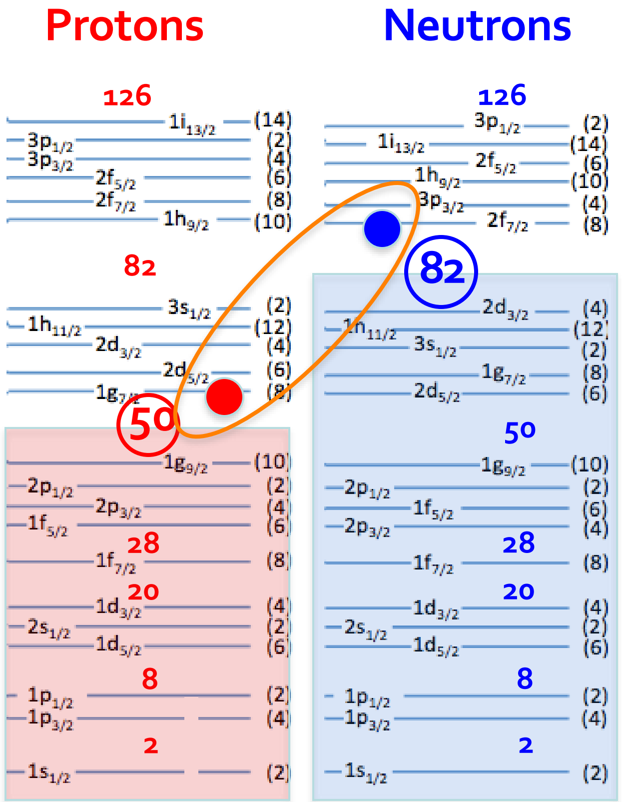


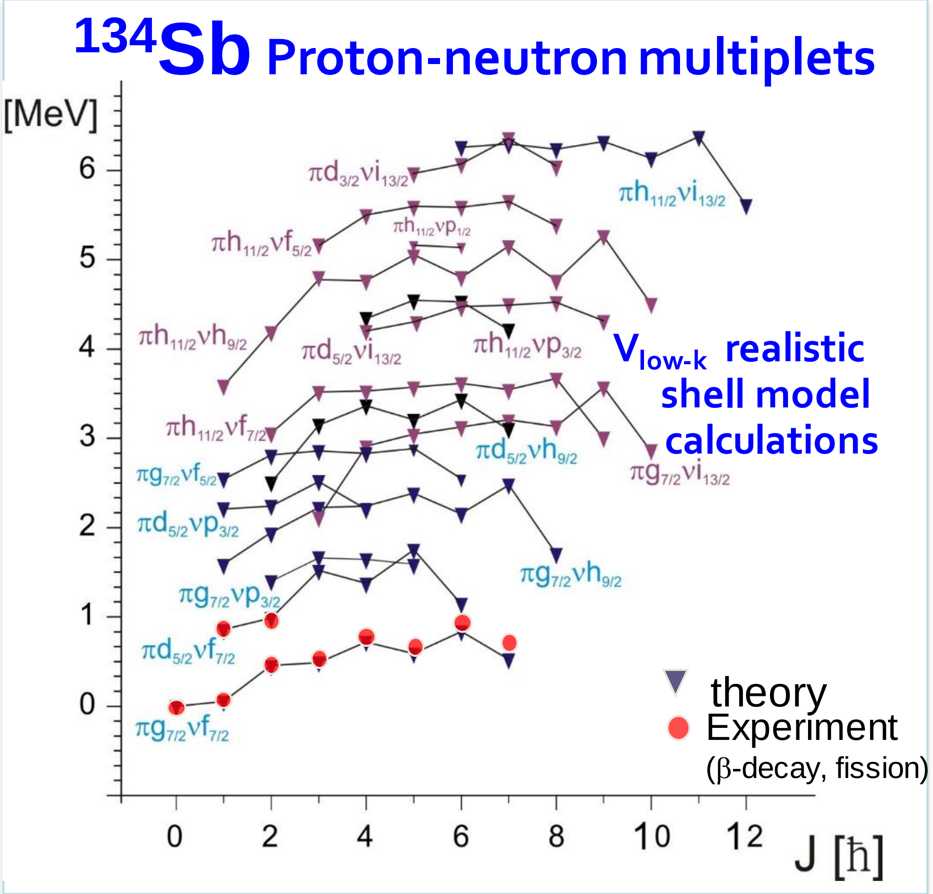
FROZEN COUPLINGS

^{134}Sb = ^{132}Sn + 1π + 1ν

→ Two-Body Matrix Elements

L. Coraggio, A. Covello, A. Gargano, N. Itaco, PRC **80**, 021305(R) (2009)





^{134}Sb Proton-neutron multiplets

$V_{low\text{-}k}$ realistic shell model calculations

^{132}Sb = ^{130}Sn + 1π + 1ν
^{134}Sb = ^{132}Sn + 1π + 1ν

LOI: *$^{132\text{-}134}$Sb (N. Cieplicka, S. Leoni, B. Fornal)*

Conclusions

Theoretical development plan:

- New theoretical developments to **link nuclear Hamiltonian** to **QCD**
  - calculation method which also provides uncertainties

- **Precision measurements** of observables for a meaningful comparison with theory:
  - **electromagnetic** and **nuclear** interaction observables
  - measuring transfer **cross sections** with the **sensitivity** requested by models

Mid-term experimental plan : «designer nuclei»

- Shell-evolution around N=50:
  - U, Pb fusion-fission with **AGATA+PRISMA-Plunger**
  - SPES 1^+ β decay GT strength with **β-decay station**
  - SPES beams with **AGATA+ SPIDER-GRIT-Cryotarget CTADIR- Plunger**

- Shape coexistence and deformation around N=60-N=80
  - SPES 1^+ β decay E0 and fast-timing with **β-decay station- SLICES**
  - SPES beams with **AGATA+ SPIDER-GRIT-Cryotarget CTADIR- Plunger**

- Shell-evolution around N=82:
  - SPES beams with - **AGATA+ SPIDER-GRIT-Cryotarget CTADIR- Plunger**
    - Active target

Outline

TOPICS	A	B	C
New theory developements for shell structure	EDF approaches extended to the N=50 and N=82 odd nuclei	Ab-initio approaches extended to the N=50 and N=82 regions, calculations of spectroscopic observables	Study of the single-particle strength distribution in energy and spectroscopic amplitude
Shell-evolution around N=50: shape coexistence and gap reduction towards 78Ni	Fusion-fission reactions with stable Pb, U beams: lifetimes and spectroscopy in 80Zn,81Ga, 79Cu and nearby isotopes	Beta-delayed e-(E0), neutron and gamma-ray spectroscopy around N=50 for shape coexistence: 80,82Ga	•Coulex of isomeric intruder states in 79Zn, 81Ga •(d,p), (d,t) on 80Zn-84Se •(3He,d) on 80Zn-84Se •Coulex and (d,p) transfer on the intruder isomer in 79Zn, 81Ge
Shape coexistence and type II shell evolution around N=60 in Zr, Sr		•Beta-delayed e$^-$(E0) spectroscopy in 96Sr •Beta-delayed gamma-ray spectroscopy with fast-timing in Kr, Zr, isotopes around A=100	•Coulex of 96,97Y, 96Sr •(d,p) transfer on deformed nuclei: 94,95,96Kr, 96,97,98Sr
Shell-evolution at N=82 around 132Sn			•Coluex of 126;128Cd,136Te and 135Sb •(d,p), (d,t) on 132,134Sn •(3He,d) on 132,134Sn - 7Li cluster transfer on 132,1342Sb
Lifetimes after transfer reactions for interplay of deformation and single-particle			Plunger device with: •(d,p), (d,t) on 80Zn-84Se •(d,p) transfer on deformed nuclei: 94,95,96Kr, 96,97,98Sr •(d,p), (d,t) on 132,134Sn •- 7Li cluster transfer on 132,1342Sb

A: stable beams (2022)

B: 1+ SPES beams (2024)

C: SPES beams (2025)

Thanks for the attention !