Research at LNL: challenges to theory

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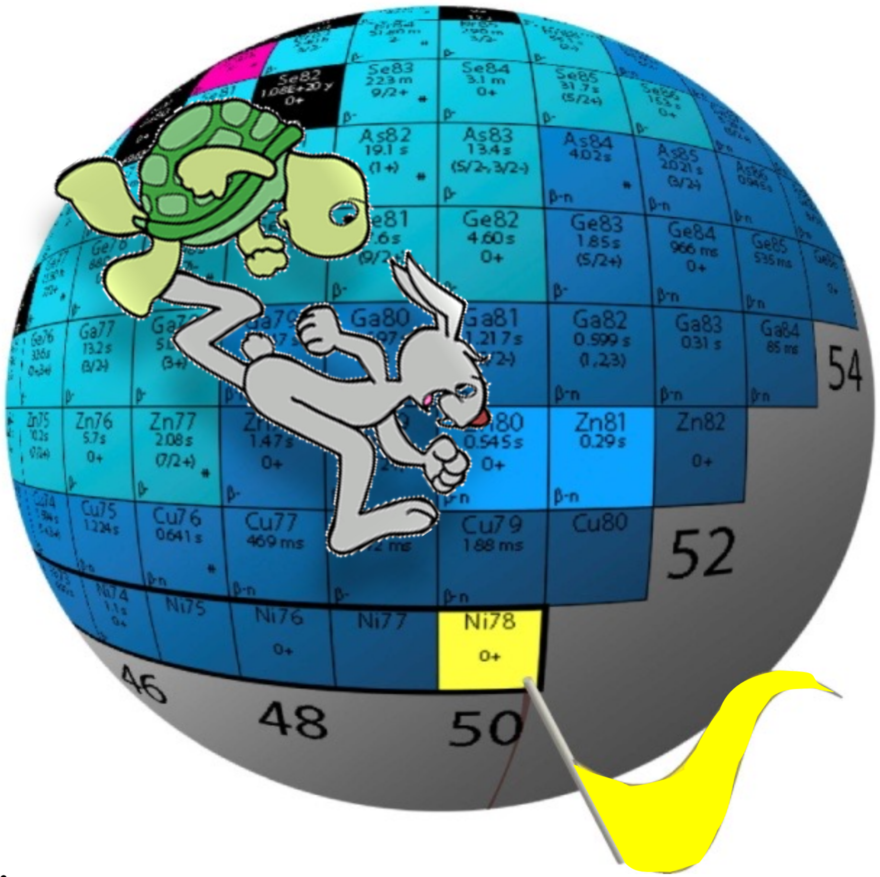
«individuare dei temi di ricerca
di interesse dei laboratori in cui il
rapporto con i teorici sia particolarmente
importante (3-4 anni)»

Istituto Nazionale di Fisica Nucleare

OUTLINE

- **Nuclear spectroscopy observables**
  - **- γ-ray spectroscopy**
  - **- electromagnetic transition rates**
- **Multi-nucleon transfer reactions**
- **Sub-barrier fusion**
- **SPES: future**
  - **- direct reactions**
  - **- nuclear spectroscopy**
  - **- β decay**
- **Nuclear astrophysics**



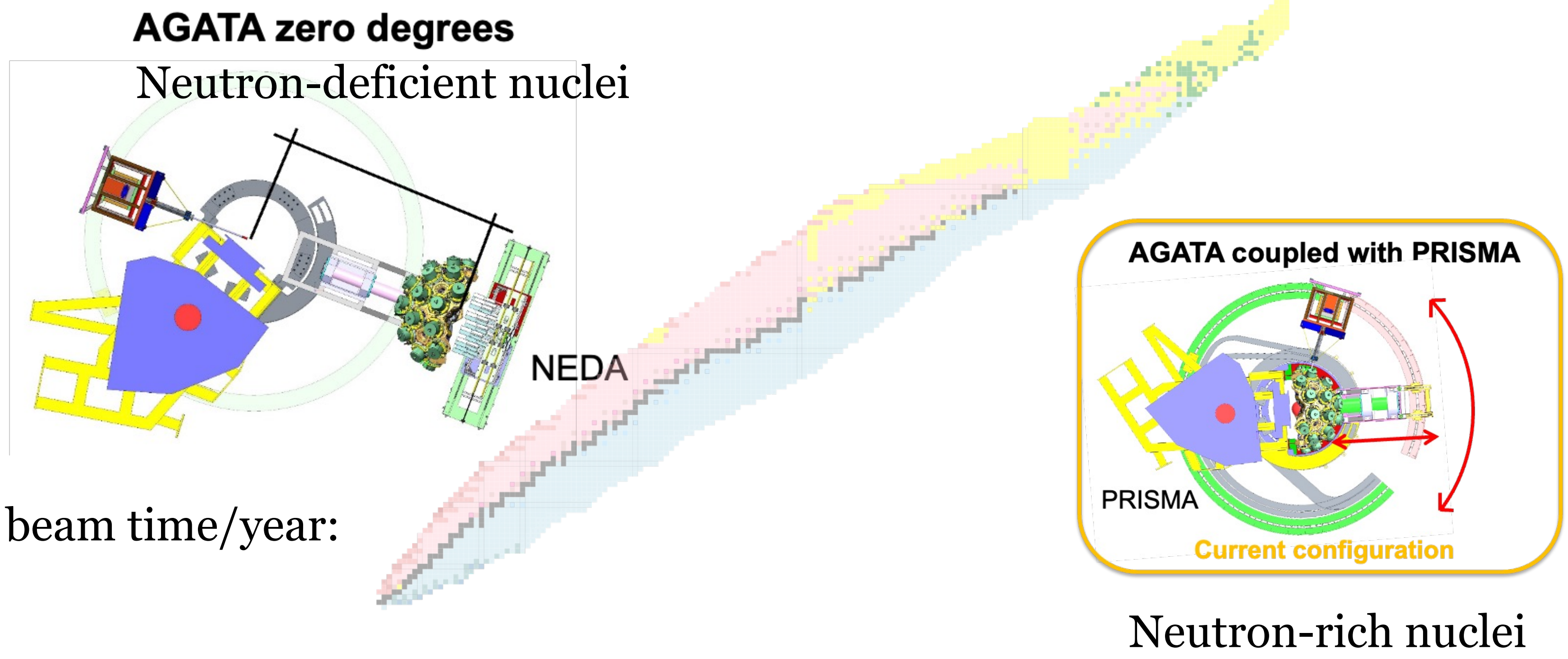
DISCLAIMER.

- «Taste» of what will be done at LNL in 3-4 years
- Perspectives on the future

➢ **Specific points of collaboration with theoreticians**

The key instruments at LNL 2023-2027

- AGATA is a state-of-the-art γ-ray tracking array
  - high resolution γ-ray spectroscopy
  - lifetimes measurements: RDDS, DSAM: 1 ns – few fs



- Several thousands of hours of beam time/year:
  - 20 experiments/year

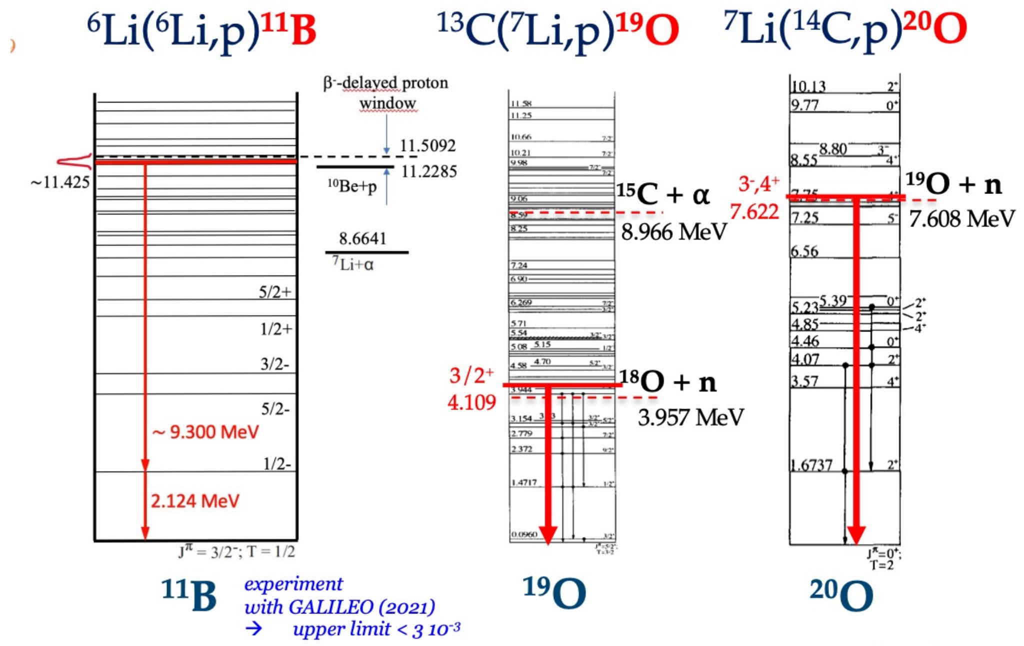
Future (mid term): neutron rich ISOL beams from SPES (AGATA-GRIT)

Nuclear spectroscopy

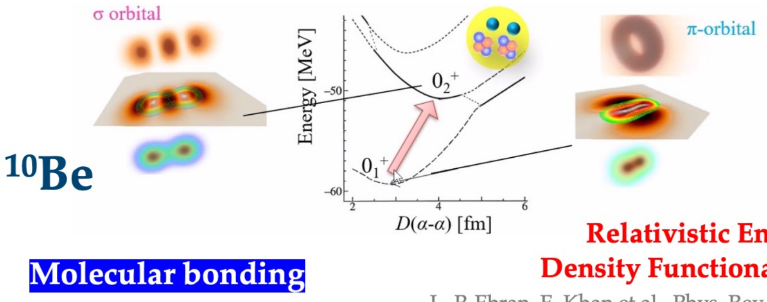
Spectroscopy in light nuclei

γ from unbound states

Courtesy of S. Bottoni



Molecular states



J. -P. Ebran, E. Khan et al., Phys. Rev. C **90**, 054329 (2014)

Sensitivity to inelastic cross sections

- Transition strength from π- to σ-type molecular states
- Di-neutron configuration

Courtesy of S. Bottoni

Possible measurements

Inelastic excitation of ^{10}Be SPES beam

- ^{10}Be(α,α') or ^{10}Be(d,d')
  probing molecular states
  γ detection needed

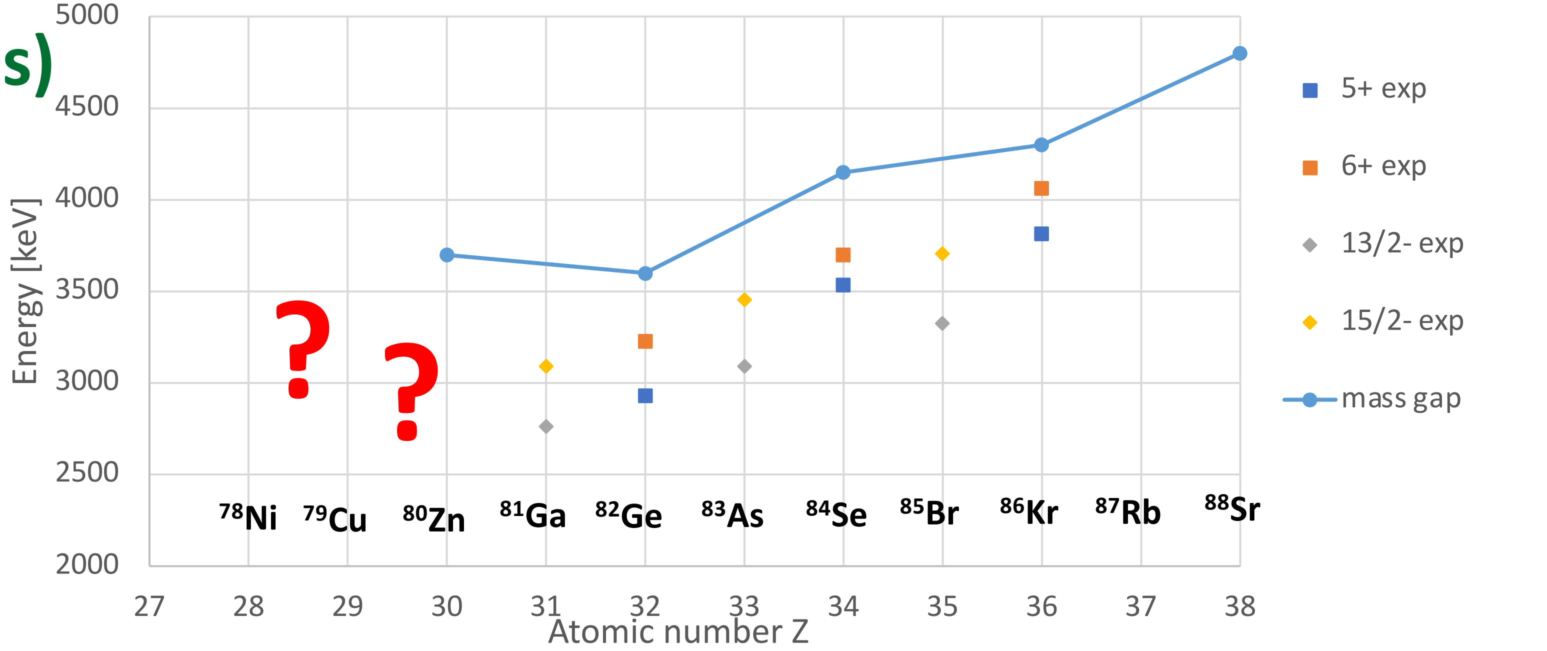
- ^{10}Be(p,p')
  probing di-neutron correlations
  γ detection needed

➢ Models treating the coupling the continuum, like the Shell Model Embedded in the Continuum (SMEC)

➢ EDF models, cluster shell model

Excited states in nuclei for shell structure

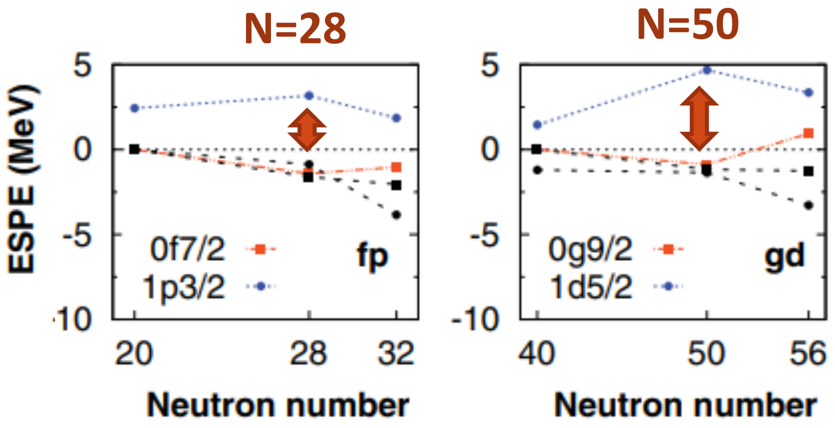
The N=50 shell gap (stable beams)



- **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 ?</u>
<u>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

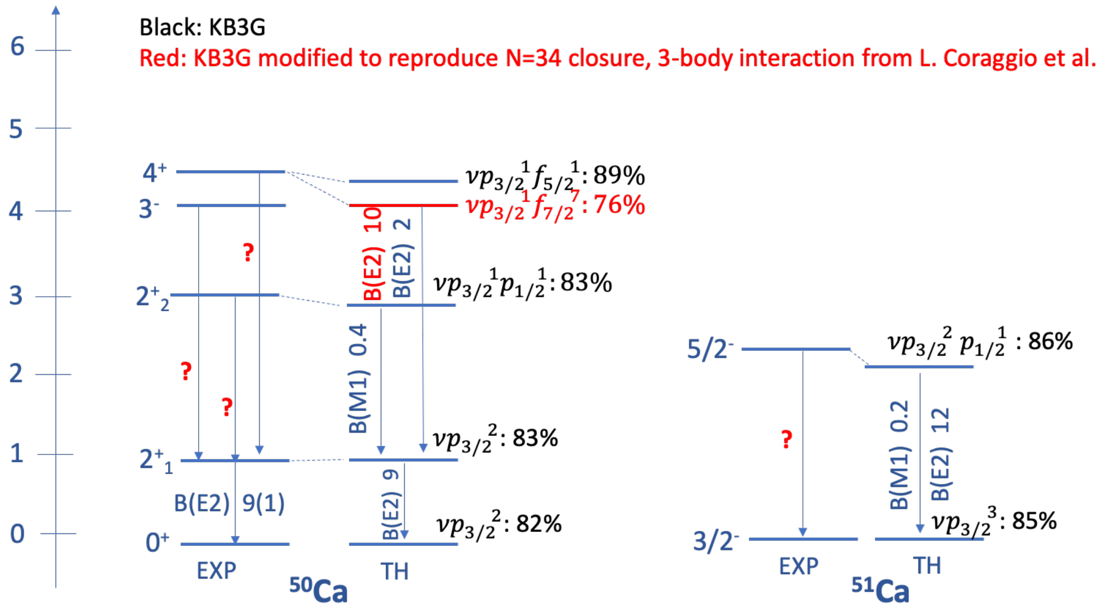
- LSSM calculation breaking magic cores
- Hybrid models for core coupling ?
- Ab-inito method as a different approach

Lifetimes of excited levels in “semi-magic” nuclei (I)

Shell evolution from lifetimes

- B(E1,E2,E3), B(M1) from «shell-model» states to probe the predicted wave function
- ^{26}Mg-^{36}S region (N=20 IoI)
- ^{48}Ca region (pf shell in exotic nuclei)
- ^{68}Ni region (shape coexistence)
- Sn isotopes

Shell structure beyond N=28

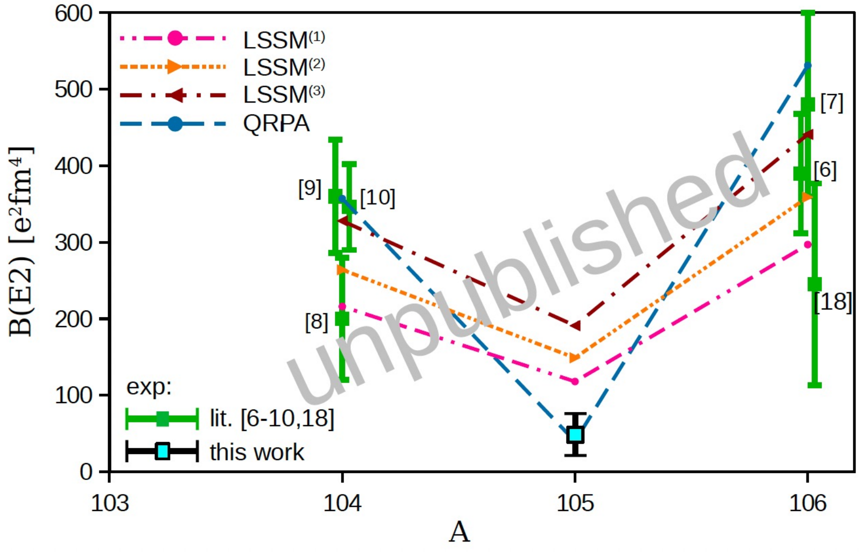


- ➢ Need for LSSM, ab-initio, EDF calculations with em strengths.
- ➢ Hybrid models for core-coupling states ?

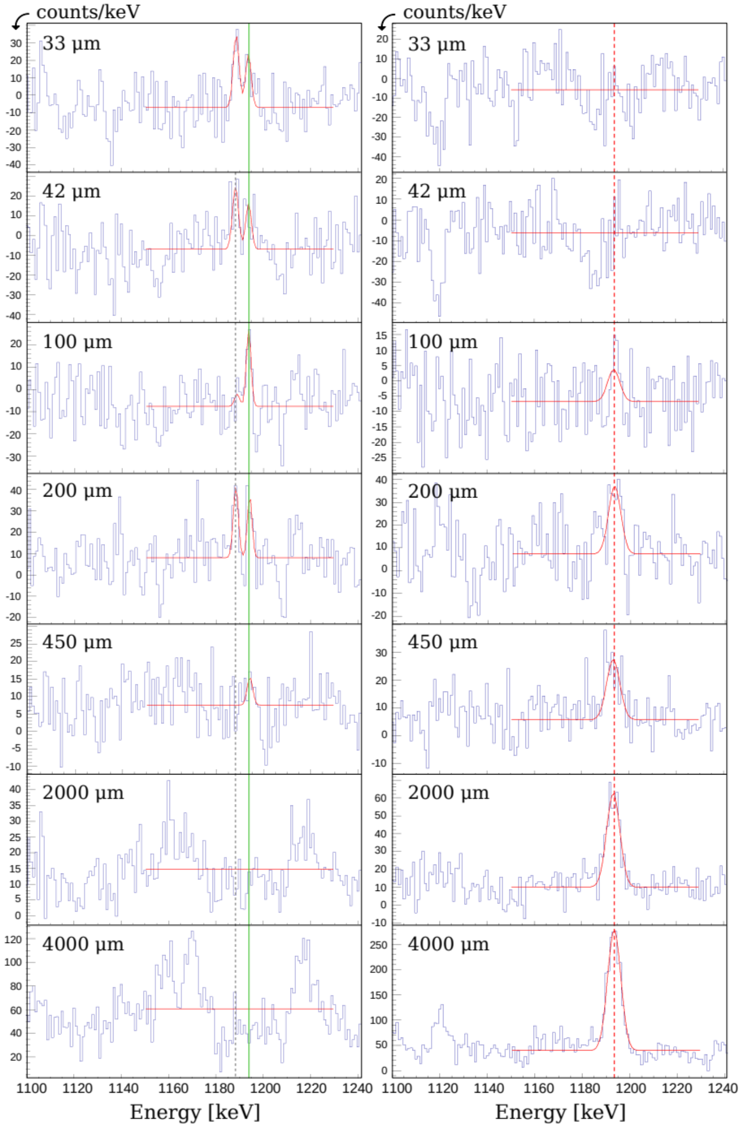
Lifetimes of excited levels in “semi-magic” nuclei (II)

Shell structure around ^{100}Sn

- Level structure, B(E2) and B(M1) in $^{105,103}Sn$ to study the Z=N=50 core breaking with GALILEO



G. Pasqualato, A. Gottardo, et al., submitted to PLB

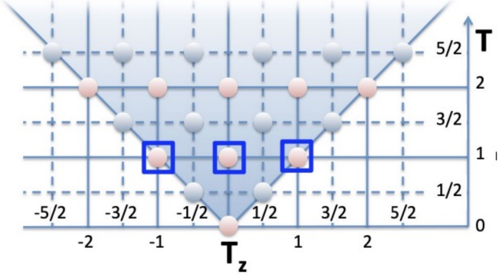


➢ Need for LSSM, ab-initio, EDF calculations with em strengths.

➢ Hybrid models for core-coupling states ?

Excited states and lifetimes in N=Z nuclei

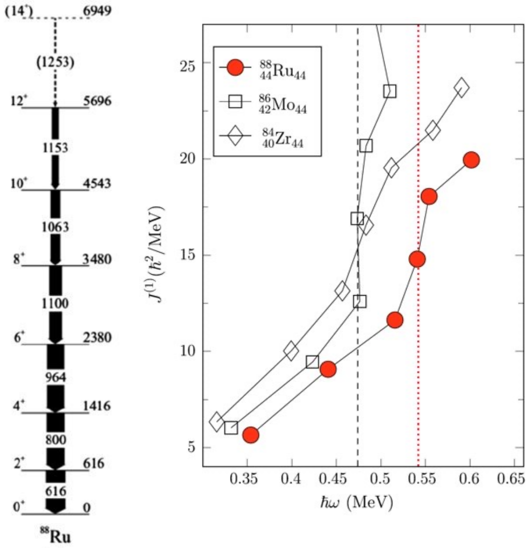
Isospin symmetry breaking



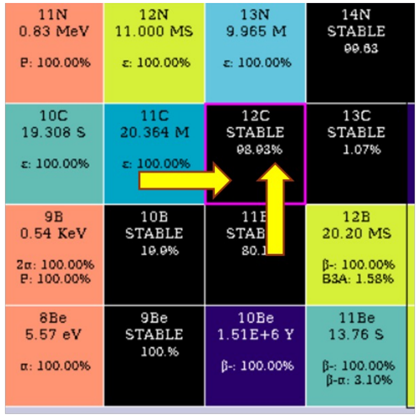
Lifetime measurements of the 2+ state in T=1 isobaric triplets
Stable beams
AGATA + NEDA + plunger

Courtesy of S. Lenzi

T=0 np in ^{88}Ru

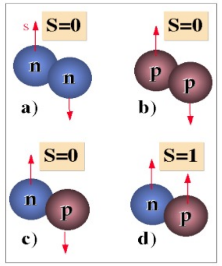


^{11}C - ^{11}B



^{11}C(d,p)^{12}C ^{11}B(d,n)^{12}C

pn T=0 paring and quarteting



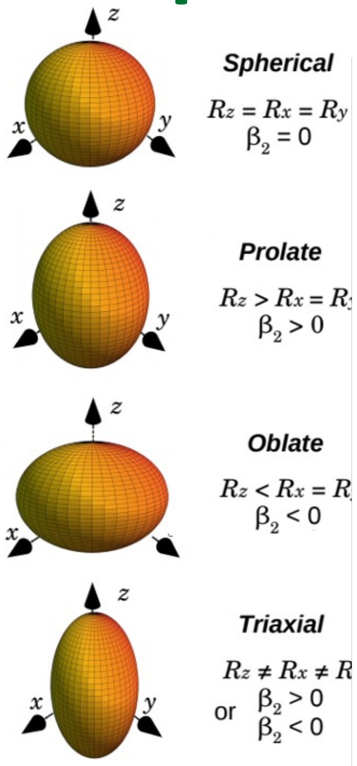
Transfer reactions
(^{3}He,p), (^{4}He,d), (^{6}Li,d)
Stable beams (*sd* shell)
SPES beams (*fp* shell)
GRIT+ Ge det + recoil det.

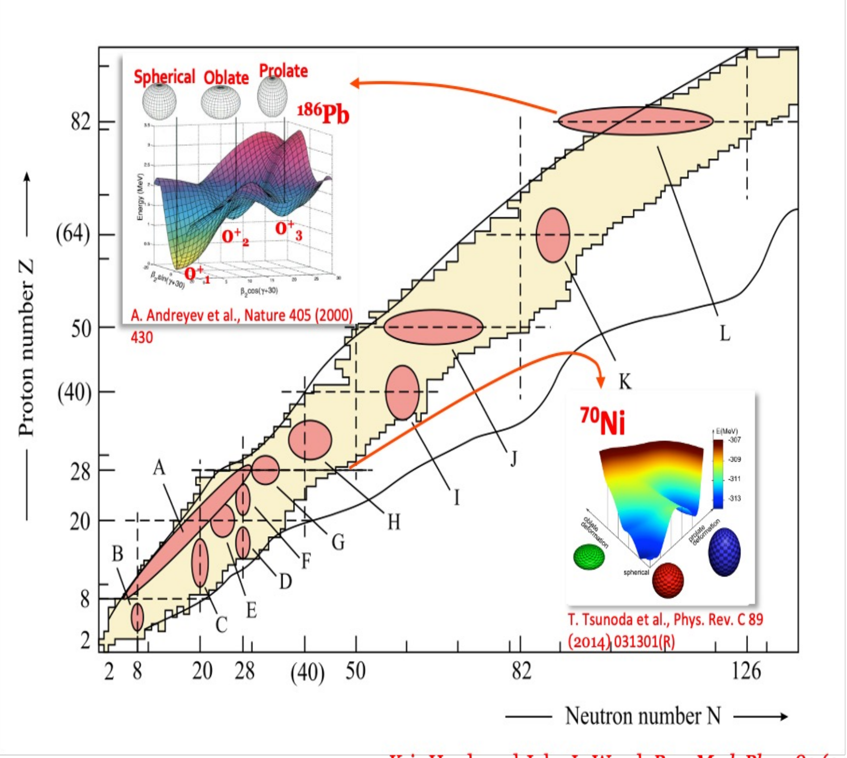
- Fusion-evaporation reactions (-2n evaporation channels): sd, fpg. shell until the ^{100}Sn region. N=Z ^{80}Zr, ^{84}Mo, ^{88}Ru, ^{92}Pd, ^{96}Cd to be studied soon.
- Deuteron transfer with ^{3}He targets (^{3}He,n)
- Excited levels, spectroscopic factors, em transition strengths

➢ Need for LSSM, ab-initio calculations with em strengths, with specific understanding of isospin breaking terms in N=Z nuclei

B(E2,E3) values in collective states

Shape coexistence, deformation



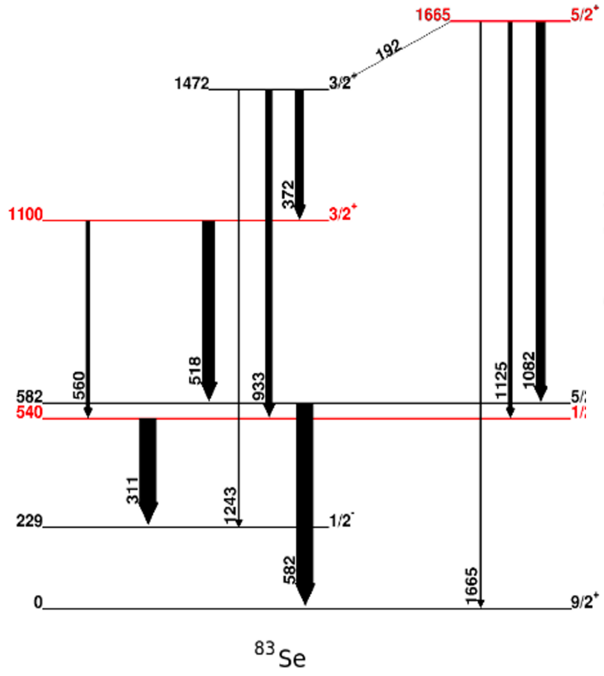


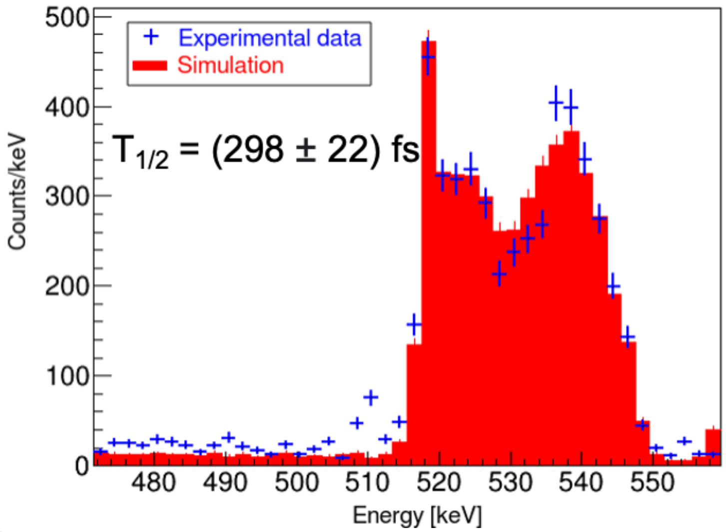
Kris Heyde and John L. Wood, *Rev. Mod. Phys.* 83 (2011) 4

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

Shape coexistence at N=50

Intruder states lowering in energy, predicted deformed second minimum



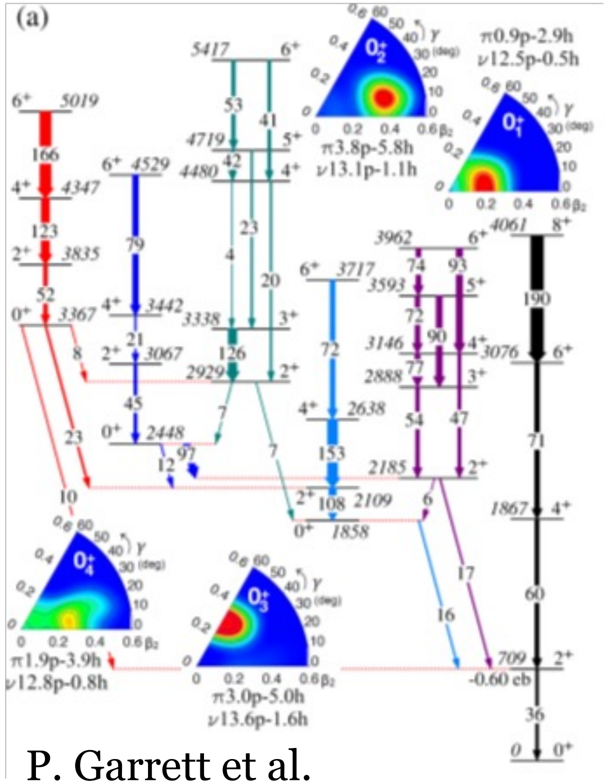


- ➢ EDF calculations with projection on angular momentum for odd nuclei

Deformed open shell nuclei

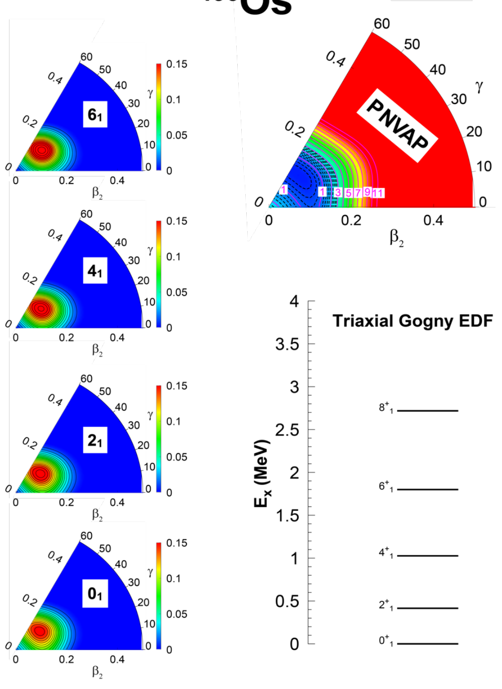
Deformation in heavy nuclei

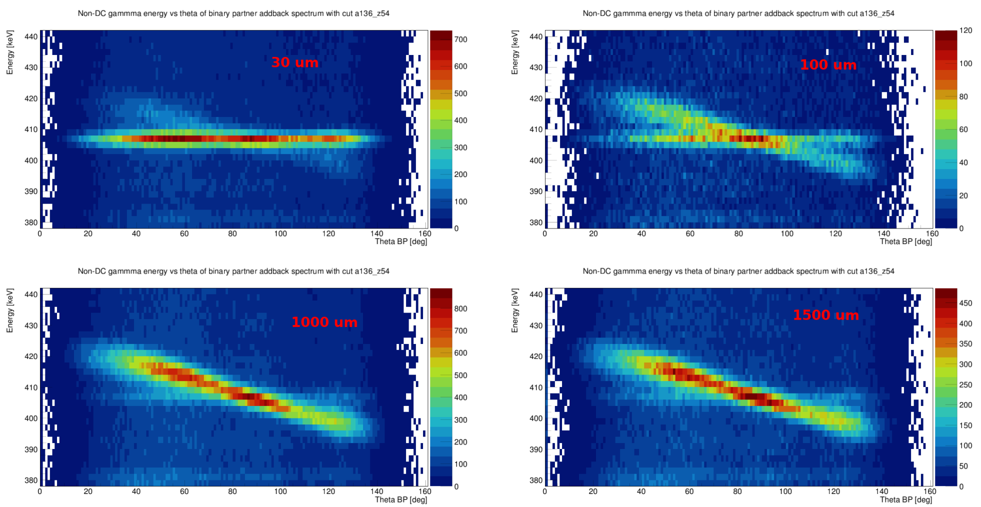
^{110}Cd



P. Garrett et al.

^{196}Os





^{196}Os, ^{200}Pt lifetime measurements

- Shape evolution along chain of isotopes:
  - Cd isotopes
  - neutron rich W, Pt, Os region
  - Zr isotopes

Courtesy of D. Brugnara, T. Rodriguez

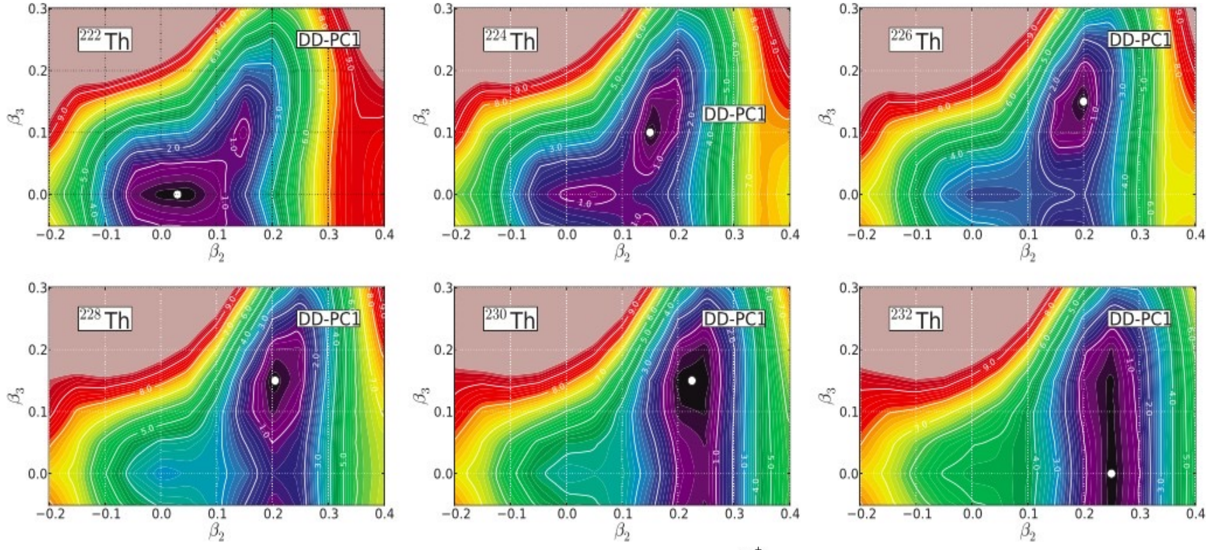
➢ Need for EDF calculations for **even-even** systems and **odd-even** systems, for level energies and em strengths

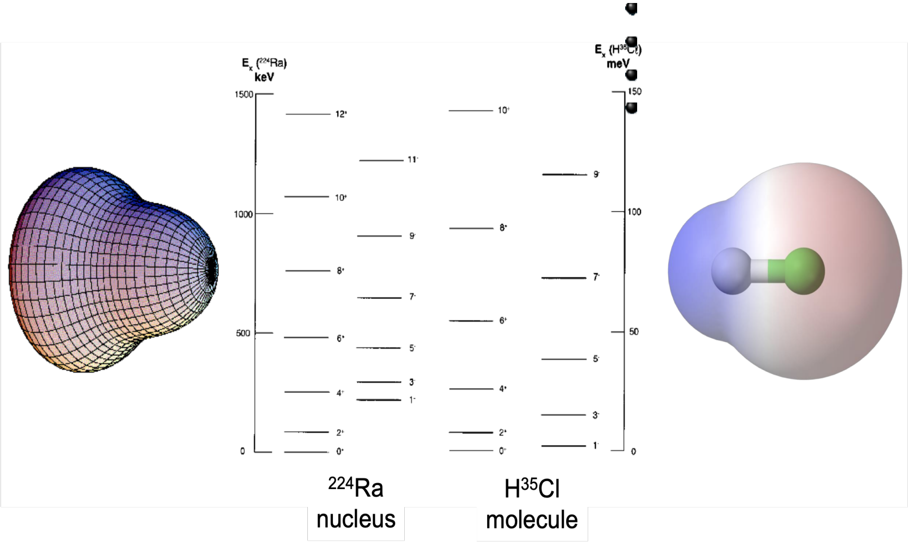
Octupoles

Pear-shaped nuclei: Increased sensibility for EDM.

Theoretical models predict:

Existence of octupole deformation in light acticinides, Coupling of quadrupole and octupole deformations

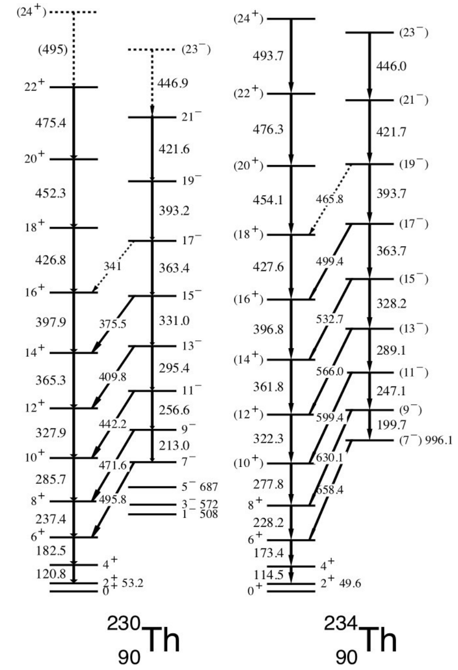




L. P. Gaffney et al., Nature **497**, 199 (2013)

Experimentally:

Alternating negative parity band Parity doublets in odd-A nuclei Enhanced E1 transitions Collective E3 transitions

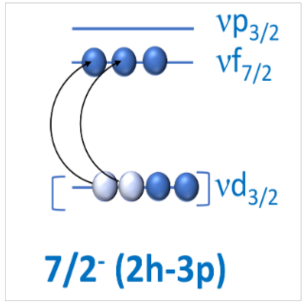


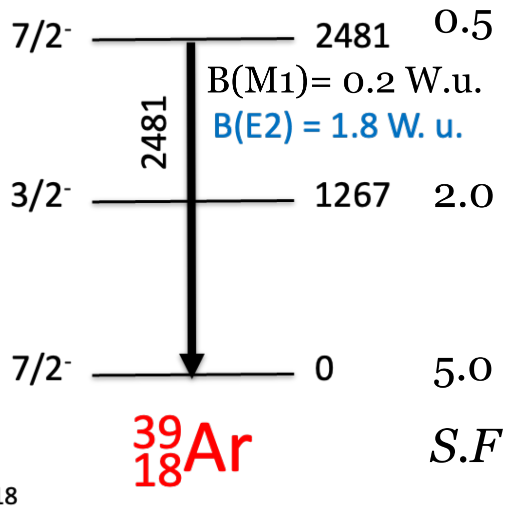
➢ Need for EDF calculations to describe octupole, quadrupole deformation

Courtesy of A. Goasduff

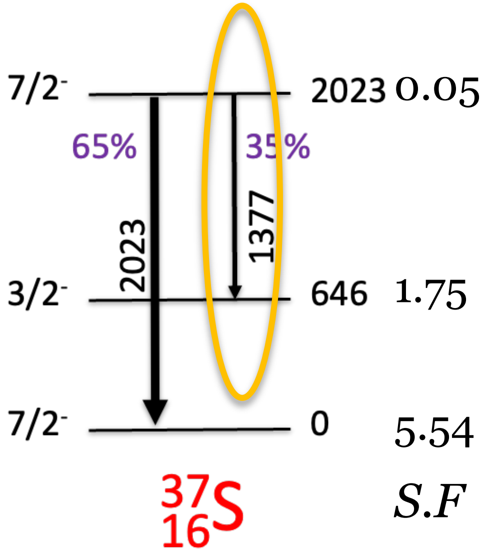
Lifetimes after transfer reactions (I)

Example: $^{36}S(d,p)^{37}S$

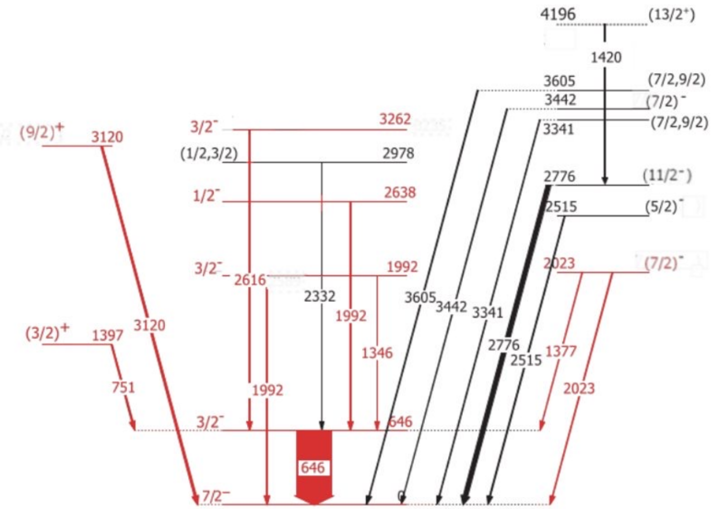


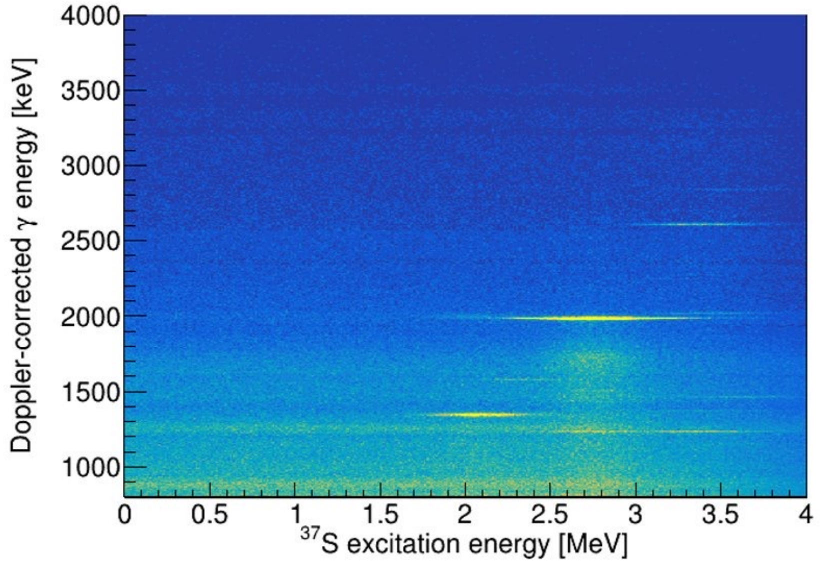


Strong BE2 appearing!



E. K. Warburton, Phys. Rev. C **35** (1987) 2278;
Phys. Rev. C **37** (1988) 754
R. Chapman et al., Phys. Rev. C **93** (2016) 044318





- Lifetimes fundamental to assess the collectivity of populated states
  - intruder states
  - core-coupled excitations (ex: 3^- coupling) in two-step process
  - mixing of single-particle states with deformed states
  - B(M1) can give complementary information on SF

Lifetimes after transfer reactions (II)

- Intruder states towards the N=20, N=28 islands of inversion
  -> B(E2) and B(M1) to detect sudden appearance of deformed bands

- Neutron/proton transfer: interaction with the other fluid may also induce collectivity to be probed with electromagnetic decay

- Large- scale phenomenological shell-model calculations (sometimes well-established Hamiltonians) for both S.F. and em strengths (effective charges in exotic nuclei)

- «Cutting-edge» calculations (for example: ab-initio methods) for S.F. and B(E2), B(M1) strengths

- Projection of ab-initio methods into the shell-model space ?

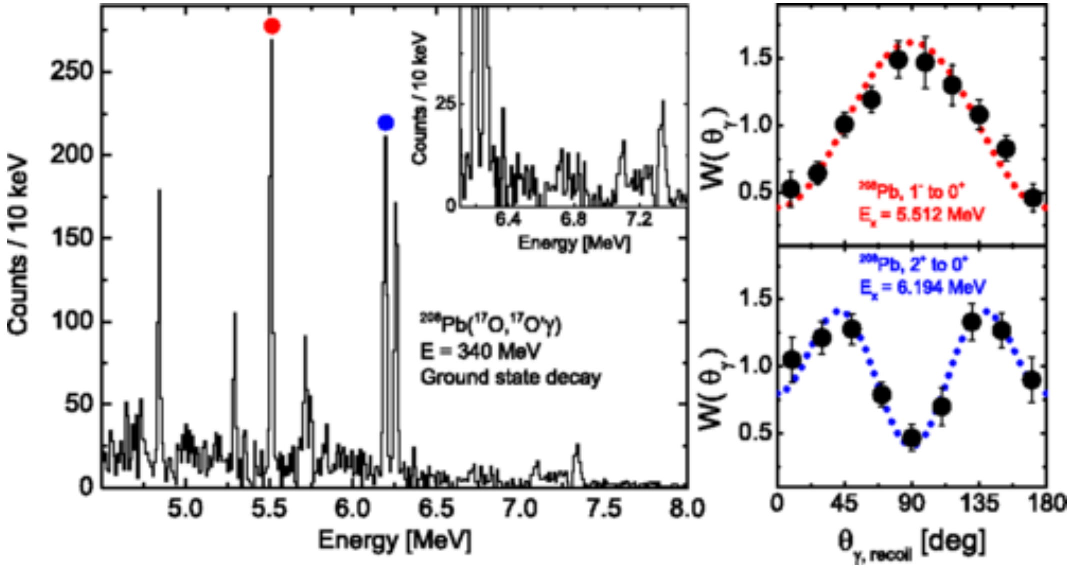
PDR, GDR, GQR, ISOMIX (stable nuclei)

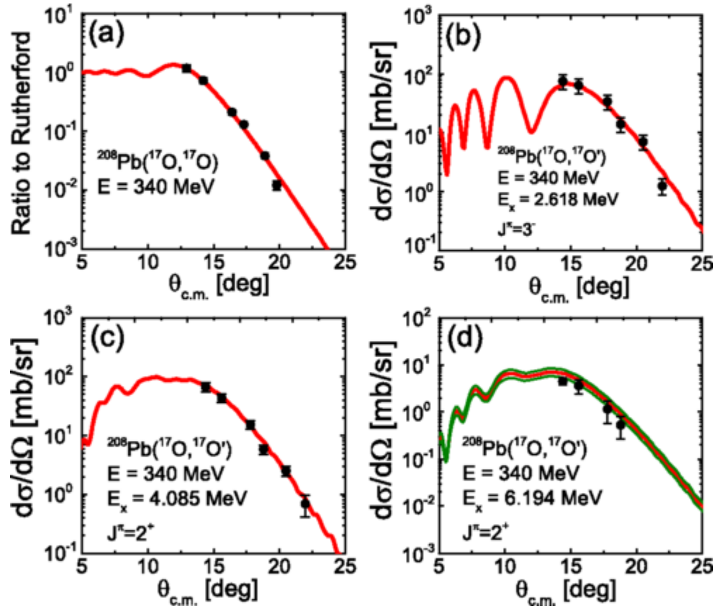
The particle decay from GR states

- ❑ GR particle decay via detection of gamma rays from residual nuclei (high efficiency of AGATA allows to determine the entry point after particle emission)

^{40}Ca, ^{24}Mg and Ni isotopes.

- ❑ Isospin mixing in N=Z nuclei





Phys. Rev. Lett. **113**, 052501 (2014)

➢ Need for EDF calculations, microscopic approaches like RPA calculations for resonances and their decay

Courtesy of F. Crespi

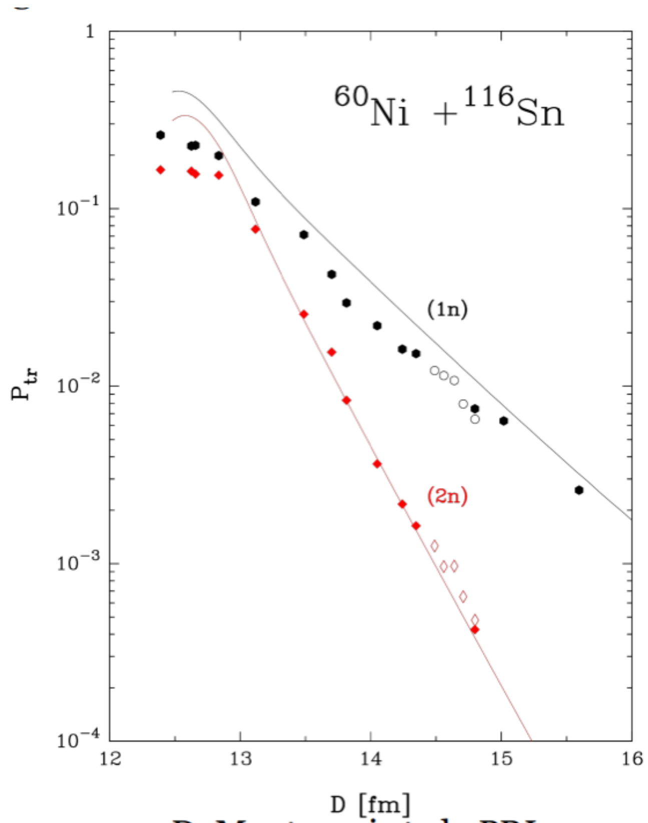
Multi-nucleon transfer

Two-nucleon transfer reactions are among the best tools to investigate correlations

- Heavy ions: simultaneous comparison of a single-nucleon transfer and a pair transfer (nn, pp and/or np)

- Studies at energies near and below the Coulomb barrier by using inverse kinematics. In the case of neutrons, an appropriate choice of the system (Qgs~Qopt~0) allows to transfer mainly to the gs (Q-value matching).
  G. Potel et al, PRC 103 (2021)

- The experimental transfer probabilities have been well reproduced, for the first time with heavy ions, in absolute value and slope, by microscopic calculations.
- Data have been interpreted as a manifestation of a nuclear Josephson effect, with Cooper pair tunnelling between the superfluid nuclei -> A specific gamma ray associated with the oscillating motion of a neutron pair is predicted



D. Montanari et al., PRL **113** 052501 (2014)

Courtesy of L. Corradi

Requests for theorists in connection with multinucleon transfer reactions

- Differential and total cross sections for multinucleon transfer channels in heavy systems from above to well below the Coulomb barrier, for the ground state to ground state transitions and transitions to excited states

- Microscopic treatment of pair modes, for both neutron and proton transfer, and their contribution to the description of the main experimental observables (A, Z distributions, cross sections, Q-values)

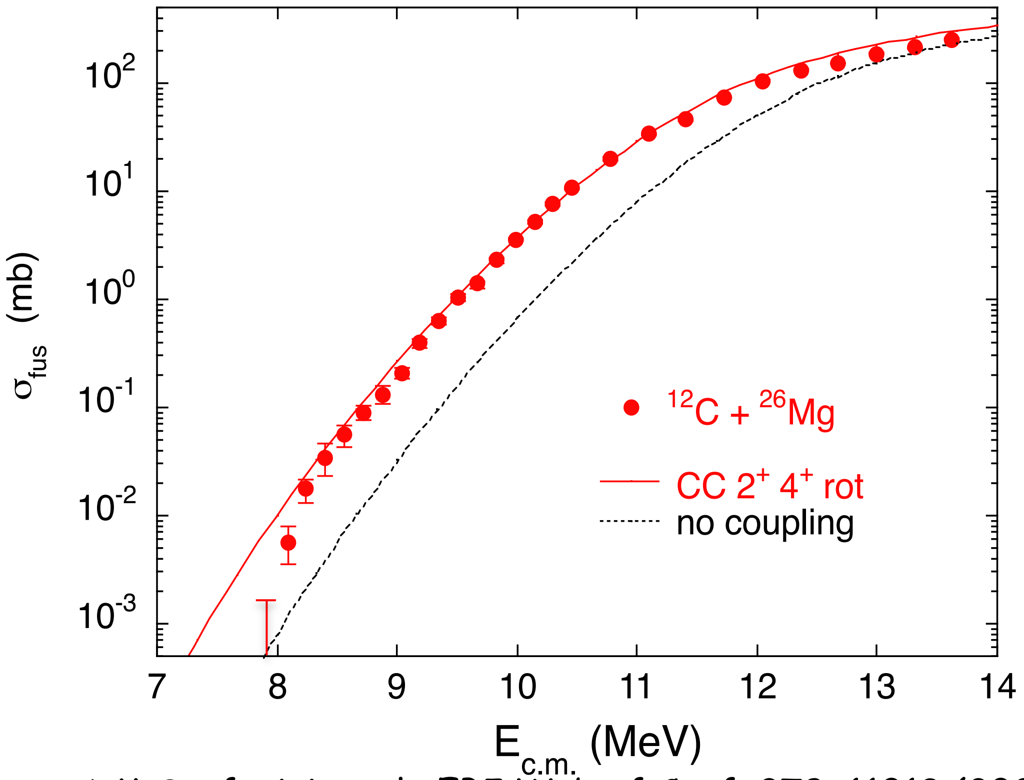
- Gamma ray strength and gamma-ray angular distribution associated to the nuclear Josephson effect for heavy systems

- Possibility to extract the neutron density distribution in neutron-rich nuclei starting from cross section measurements performed at sub-barrier energies

Sub-barrier fusion

Heavy-Ion fusion excitation functions far below the barrier

the hindrance phenomenon



A.M.Stefanini et al., EPJ Web of Conf. 279, 11013 (2023)

The existence of fusion hindrance in the light heavy-ion systems of astrophysical interest is not well established nor understood

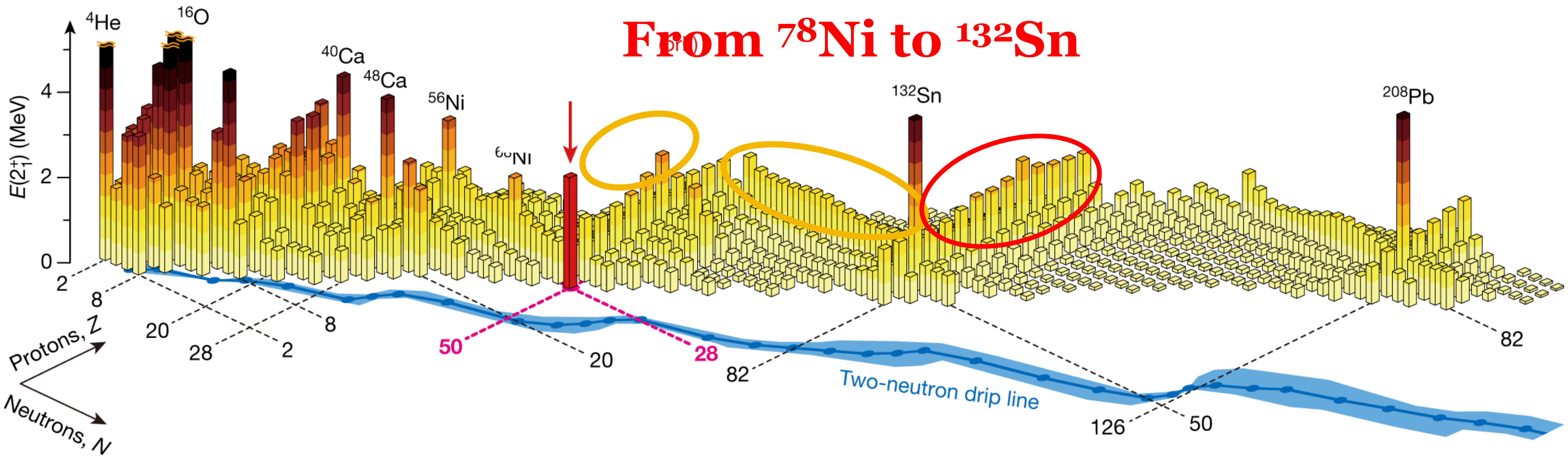
CC calculations performed with the code CCFULL, requiring the information on the nuclear structure of the two colliding nuclei

- The physics underlying the hindrance phenomenon is not yet clarified. Recent theoretical developments imply the influence of the Pauli exclusion principle, or an adiabatic approach where the ion-ion interaction evolves from a two-body to a one-body potential.

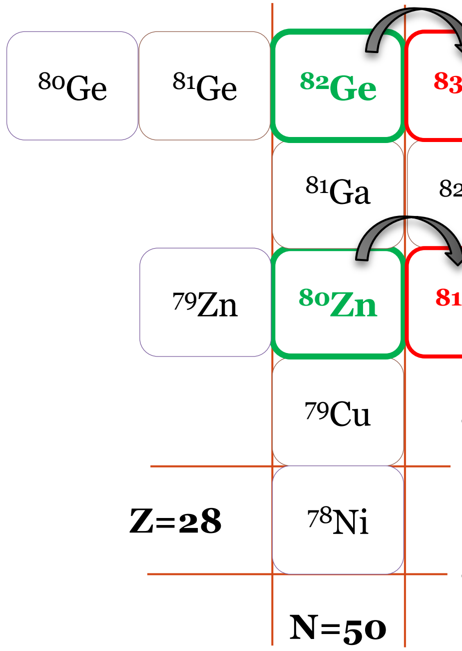
C.Simenel et al., PRC95, 031601(R) (2017)
T. Ichikawa, PRC92, 064604 (2015)

Courtesy of A. Stefanini. G. Montagnoli

Direct reactions (SPES-future)

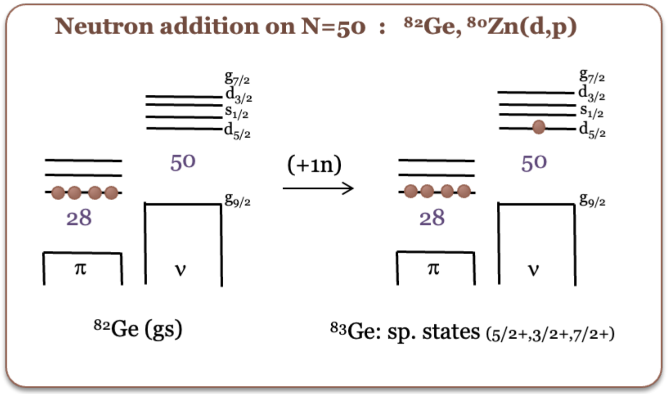


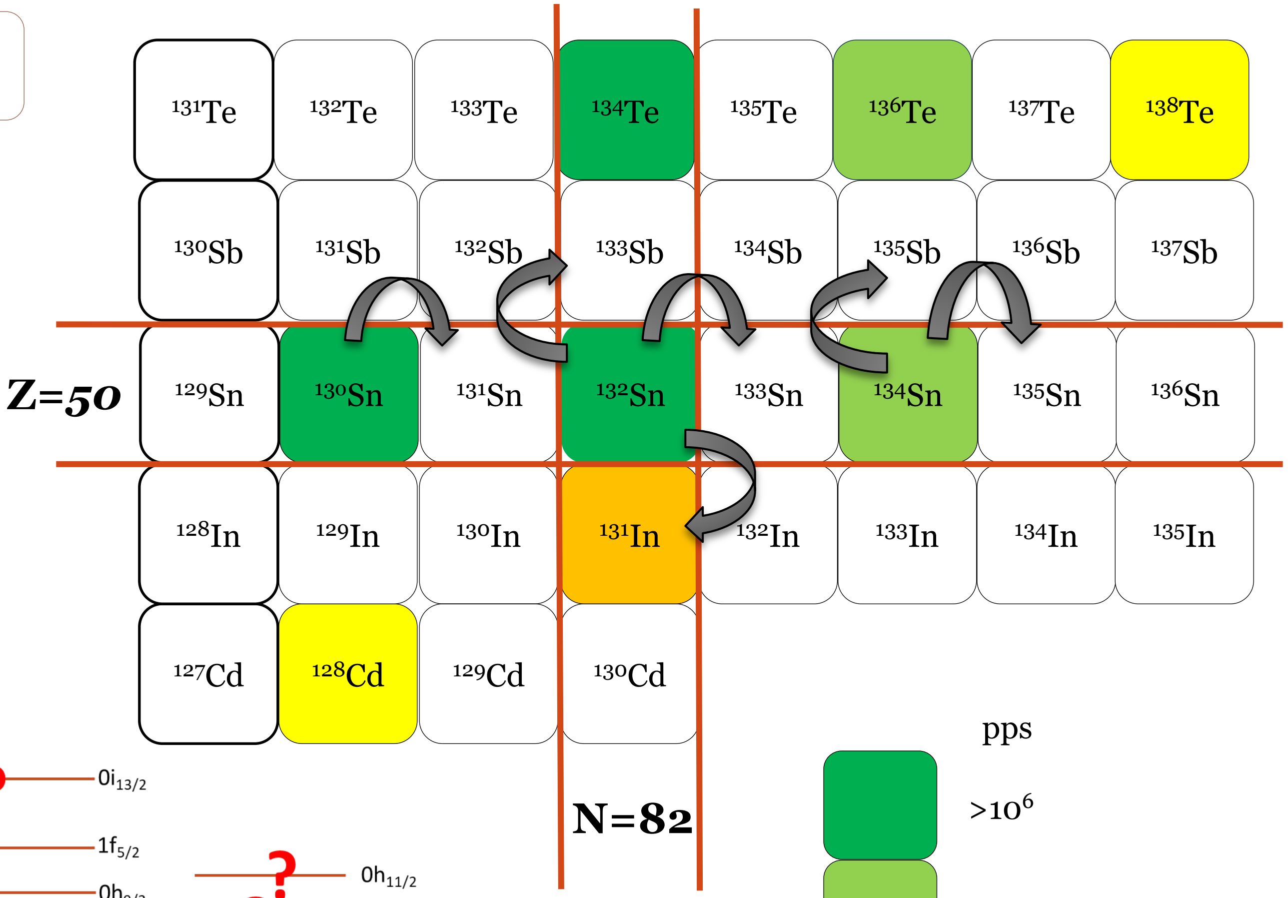
Shell evolution

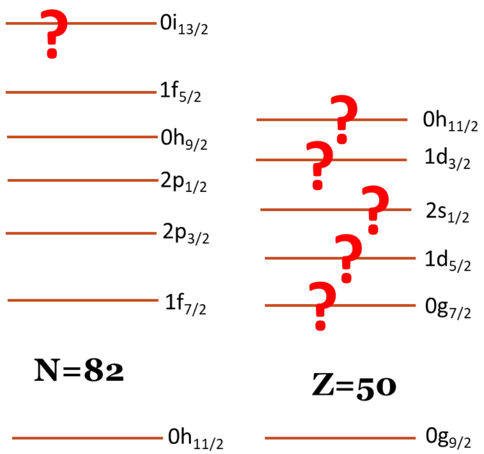


- Selectivity to n(gds)$^{+1}$ states
- Drift, spread of s.p. strength

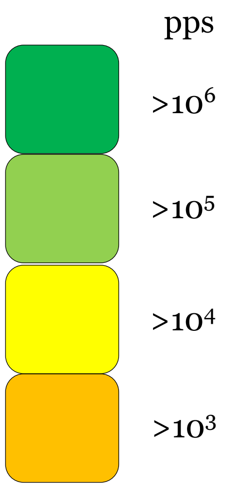
  → Cross sections -> s.p. strength





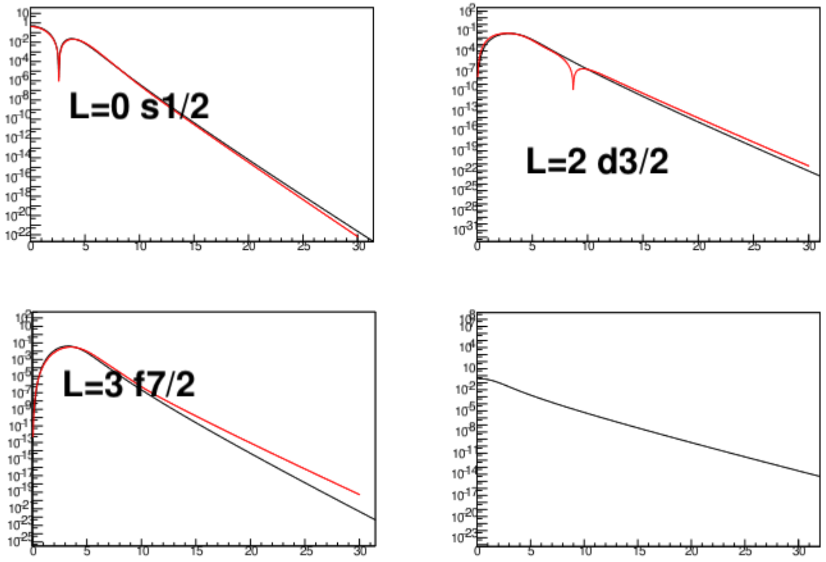


SPES beams



Direct Reaction Theory

Example: ^{46}Ar(^{3}He,d)



D. Brugnara

- Ingredients of a typical DWBA calculation:

  - Optical potentials : phenomenological or first-principle ?

  - Overlap: Wood-Saxon wave function or from theory ?

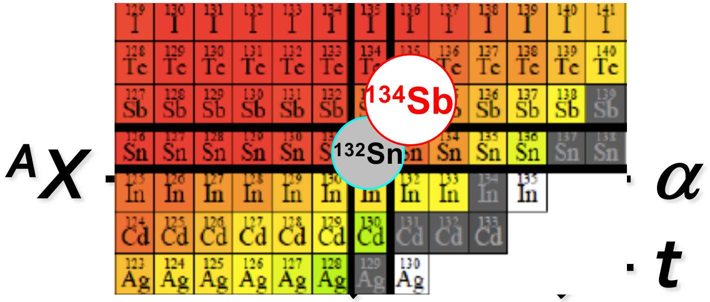
  - Structure input: spectroscopic factors

➢ A coherent theoretical scheme between reaction theory and shell structure (example: three-body effects on structure/reaction)

➢ New methods (es: ab-initio) extened to heavy nuclei (^{132}Sn) for both reaction and nuclear spectroscopy

Nuclear Spectroscopy with SPES beams

Cluster Transfer Reactions for ^{132}Sn region



Courtesy of S. Leoni

FROZEN COUPLINGS

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

$$^{132}Sb = {}^{130}Sn + 1\pi + 1\nu$$

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

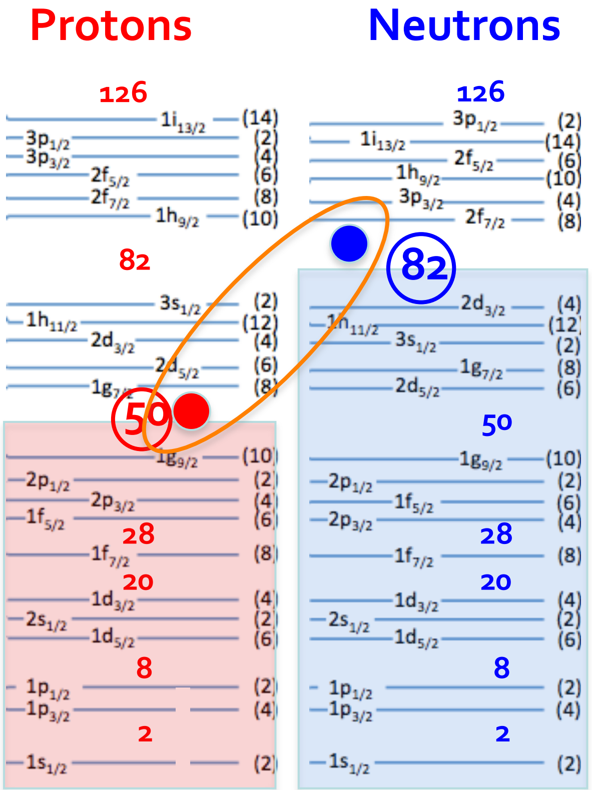
Weakly Bound Target

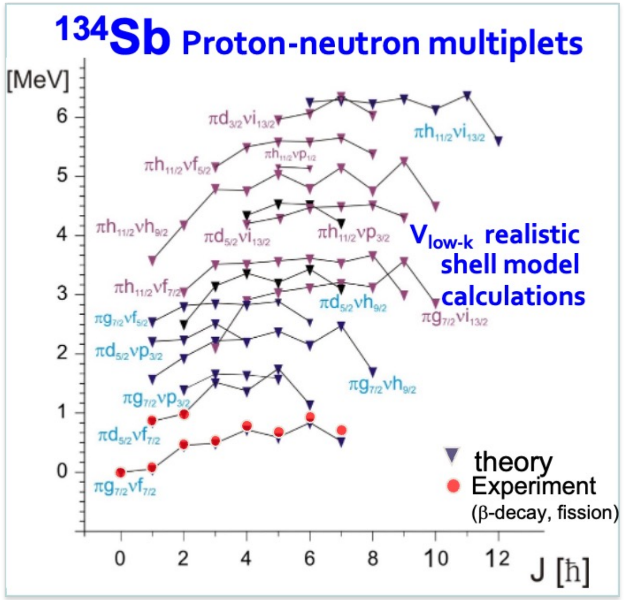
B.E.(α-t) = 2.5 MeV

Cluster Structure

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

$$\rightarrow ({}^AX + \alpha) + t$$





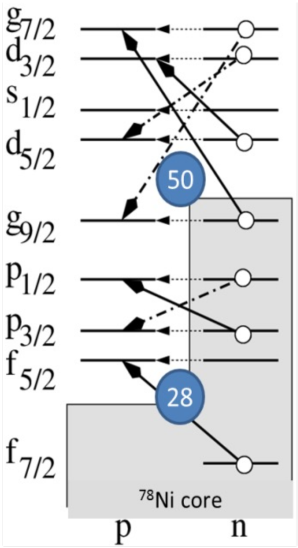
L. Coraggio, A. Covello, A. Gargano, N. Itaco, PRC **80**, 021305(R) (2009)

- Calculations for core coupling: LSSM, EDF ?
- Hybrid models to describe particle coupling to collectivity
- Reaction theory

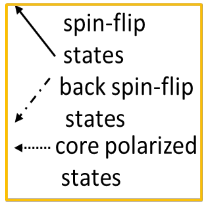
β decay

B(GT) distribution and neutron emission

β decay for N=50 shell structure

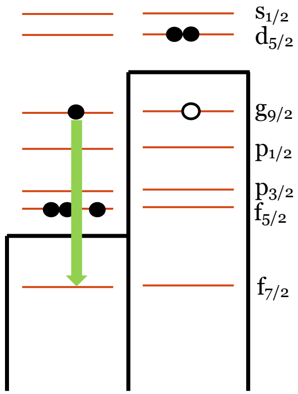


single(quasi)-particle GT transitions



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

excited configuration after GT transition

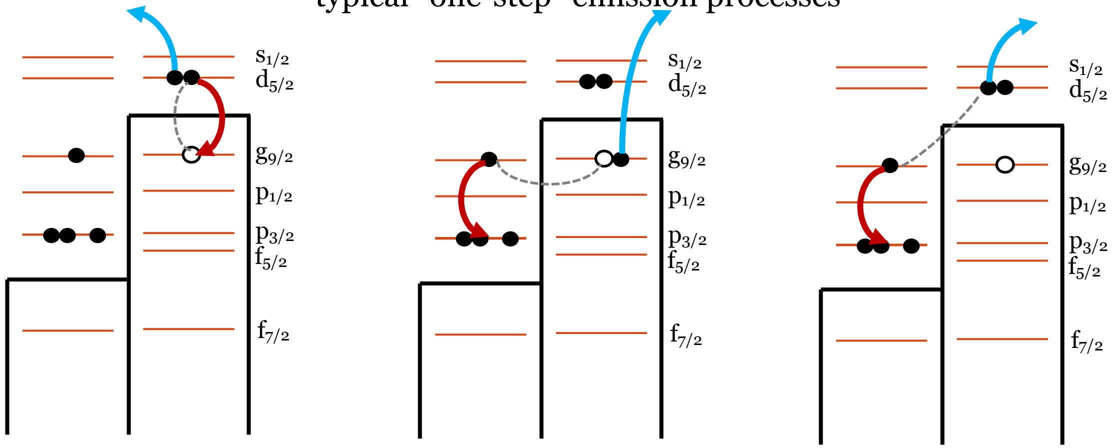


E1 partners available

all involve high ℓ($\ell \geq 2$) neutron transitions → inhibited

- **Gamow-Teller doorway states**

typical "one-step" emission processes



neutron-neutron particle-hole "collision"

proton-neutron particle-hole "collision"

proton-neutron particle-particle "collision"

- **SPES 1⁺ beams (> 10^1 pps):**

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

➢ B(GT) calculations:
- LSSM
- ab-initio ? EDF ?

Nuclear astrophysics

Nucleosynthesis up to the Iron peak

- $^{12}C+^{12}C$ VIA THE $^{20}Ne(\alpha,\alpha')^{20}Ne$ RESONANCE SCATTERING
- $^{16}O+^{16}O$ WITH SUGAR JET TARGET

Major reaction sequences:

$$^{16}O+^{16}O \rightarrow ^{32}S^* \rightarrow ^{31}S+n+1.45\ \mathrm{MeV} \quad (5\%)$$
$$\rightarrow ^{31}P+p+7.68\ \mathrm{MeV} \quad (56\%)$$
$$\rightarrow ^{30}P+d-2.41\ \mathrm{MeV} \quad (5\%)$$
$$\rightarrow ^{28}Si+\alpha+9.59\ \mathrm{MeV}. \quad (34\%)$$

plus recapture of n,p,d,α

Main products:

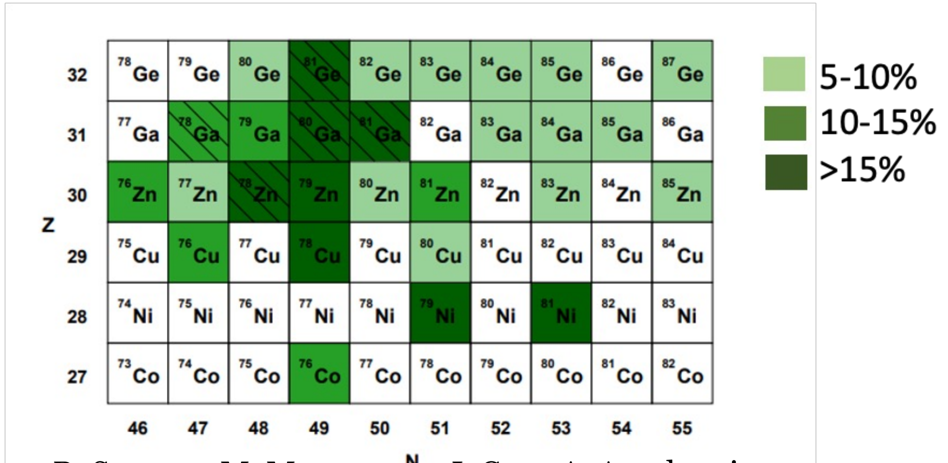
^{28}Si,^{32}S (90%) and some $^{33,34}S$, $^{35,37}Cl$, $^{36,38}Ar$, $^{39,41}K$, $^{40,42}Ca$

Courtesy of A. Caciolli

- ➢ Theory linking nuclear observables to astrophysical abundances (what observables to look at?)
- ➢ Reaction theory for light nuclei (what models ? Cluster ?)

Neutron r and s process

- Neutron capture cross sections:
  - (d,p) reactions as surrogate
- β decay data
  - half lives
  - β-delayed neutron emission
  - neutron/gamma emission competition



R. Surman, M. Mumpower, J. Cass, A. Aprahamian, Proceedings of the Fifth International Conference on ICFN5, Sanibel Island, Florida, USA, 4 – 10 November 2012

Summary

- Theoretical calculations for nuclear spectroscopy:

  - both «traditional» and «innovative» methods
  - light and heavy nuclei
  - N=Z and neutron-rich systems
  - even and odd systems
  - electromagnetic observables and Gamow-Teller

- Reaction theory for experiments:
  - from phenomenological to microscopic calculations
  - coherence with structure
  - direct process and pair transfer

Collaboration essential for:

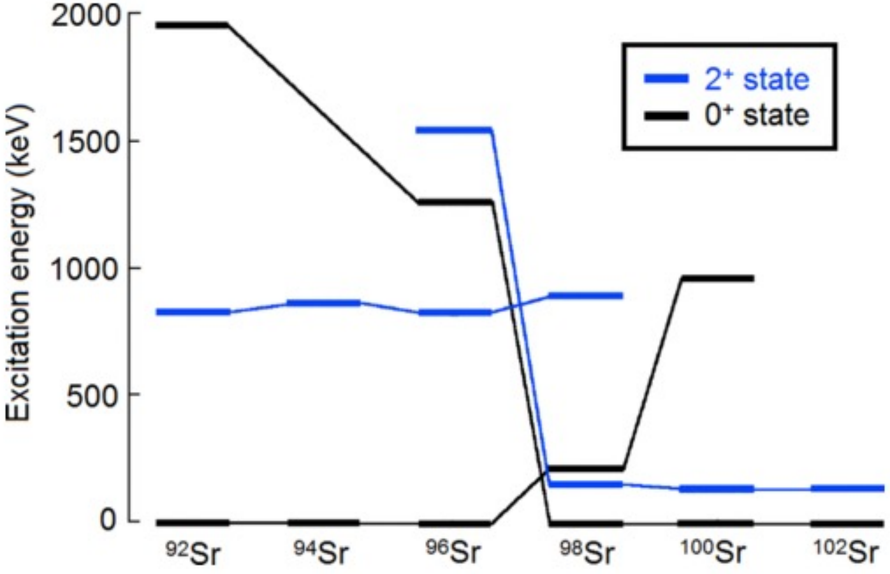
- experimental programme definition

- experimental data interpretation

THE END

THANKS FOR ATTENTION !

Direct reactions for shape coexistence/transition around N=60

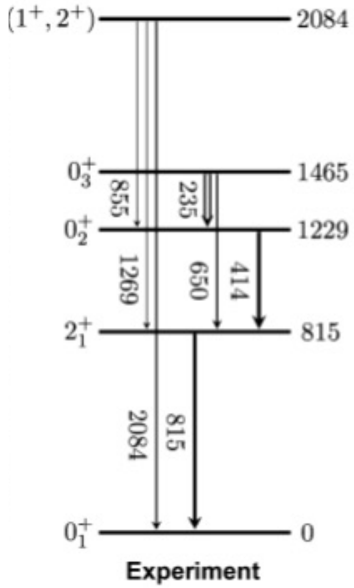


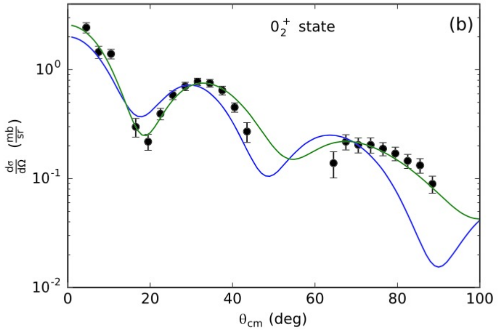
- Study of shape transition from a **single-particle perspective**
- **Microscopic nature** of coexisting 0^+, 2^+ states
- Many **unexpected observations** compared to SM prediction
- Several beams very well produced at SPES in the region (^{94,95,96}Kr, ^{96,97,98}Sr)

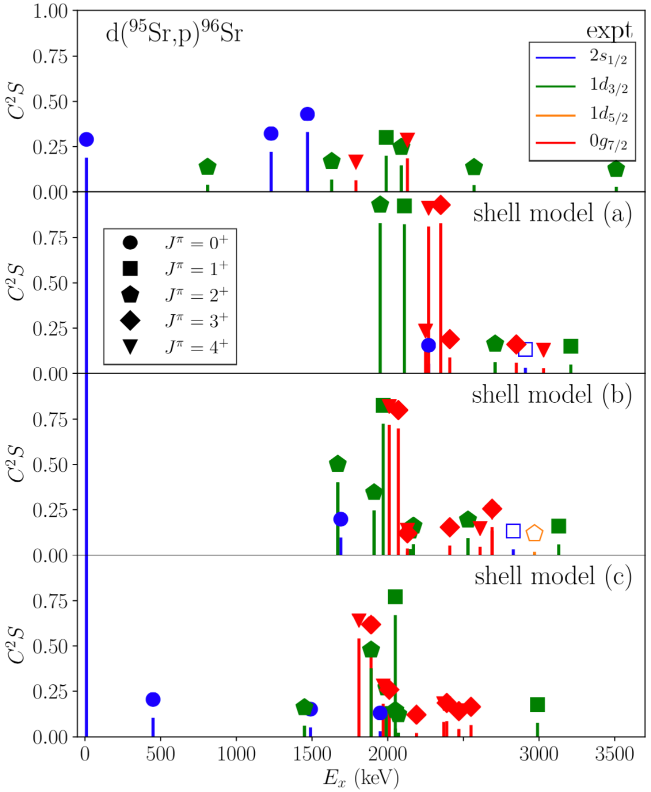
→ allow **precise studies** with part.-γ coincidences

^{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., PRC1008, 054321 (2019)

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

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
$|\psi>$

$< \psi || e r^2 || \psi>$
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

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